

An Electromagnetism-like Mechanism Algorithm Approach for Photovoltaic System Optimization

Jian Ding Tan¹, Siaw Paw Koh², Sieh Kiong Tiong³, Kharudin Ali⁴, Ying Ying Koay⁵

^{1,2,3,5}Institute of Sustainable Energy (ISE), Universiti Tenaga Nasional, 43000 Kajang, Selangor, Malaysia

⁴Faculty of Electrical and Automation Engineering Technology, TATIUC, Terengganu 24000, Malaysia

Article Info

Article history:

Received May 5, 2018

Revised Jun 26, 2018

Accepted Jul 12, 2018

Keywords:

Electromagnetism-like mechanism

Photovoltaic panel

Solar tracking system

Tilt angle

ABSTRACT

Solar energy has become one of the most studied topic in the field of renewable energy. In this paper, an artificial intelligent approach is proposed for the optimization of a photovoltaic solar energy harvesting system. An Electromagnetism-Like Mechanism Algorithm (EM) has been developed to search for the hourly optimum tilt angles for photovoltaic panels. In order to investigate the effect of the search step size on the efficiency and overall accuracy of the algorithm, the EM has also been modified into several variants with different search step size settings. Experimental findings show that EM with bigger search lengths has the advantage of reaching a near optimum tilt angle in earlier iterations but less accurate. EM with smaller step lengths, on the other hand, can hit a relatively more optimum tilt angle in the process. During the peak of the power generation at noon, EM with smaller search steps found an optimum tilt angle which yielded additional 3.17W of power compared to a fixed panel. We thus conclude that the proposed EM performs well in optimizing the tilt angle of a photovoltaic solar energy harvesting system.

Copyright © 2018 Institute of Advanced Engineering and Science.
All rights reserved.

Corresponding Author:

Jian Ding Tan,
Institute of Sustainable Energy (ISE),
Universiti Tenaga Nasional,
43000 Kajang, Selangor, Malaysia.
Email: jdtan2003@yahoo.com

1. INTRODUCTION

Renewable energy has become a term commonly known worldwide nowadays. With the fossil fuel diminishing, researchers around the globe are turning their attention into more sustainable energy sources. Among others is the solar energy [1]. Solar energy is popularly researched and implemented around the world due to its sustainability and minimal environmental damage [2]. Two systems are widely used in harvesting solar power today, namely the Solar Thermal Collector (STC) and the Photovoltaic (PV) cells. STCs convert sunlight into thermal energy while the PV cells turn solar energy directly into electricity [3].

In the literature, there are many methods of improvement to increase the energy generated by a solar harvesting system. One of the important aspects is to maximize the solar radiation that falls onto the harvesting system. The solar radiation data are not readily available for many locations in the world. Thus, it has to be estimated. A number of techniques can be found in the literature to estimation the solar radiation on tilted surface [4]-[6]. The total solar radiation that falls onto a PV panel is greatly affected by its orientation and tilt angle [7], [8]. Thus, one of the best ways to make sure maximum solar radiation onto the PV panel is to implement a solar tracker.

The contribution of this paper is threefold and can be summarized along the line as follows. Firstly, a relatively new approach, the Electromagnetism-like Mechanism algorithm (EM), has been implemented to track the maximum solar ray in order to optimize the power generated by a PV solar energy

harvesting system. To date, the implementations of the EM algorithm in solar tracking systems remain rather limited. Secondly, an analytical study on the effect of the search step length in EM has been carried out to investigate the gravity of it to the outcome of the optimization process. Finally, the performance of the modified EMs are evaluated and benchmarked. The outline of this paper can be divided into 5 main sections. The second section of the paper introduces the trajectory of the solar tracking system used in this research and the formulation of the objective function. In Section 3, the EM algorithm is discussed in details. Section 4 shows the experimental results, analysis and detailed discussion. The final section offers the conclusion.

2. TRAJECTORY OF THE SOLAR TRACKING SYSTEM

It is important to make sure a solar panel operates at an optimum tilt angle in order to expose the panel as close to its maximum solar intensity as possible. Incorrect positioning can lead to loss of potential solar power. In this research, a solar energy harvesting system with solar tracking feature is developed. A PV panel with 1.651m length and 0.9906m width is employed. A permanent magnet DC motor is installed as the main driving actuator to adjust the tilt angle (θ_s) of the solar panel within the range of 0° to 90° . The system is developed to harvest solar energy in the city of Petaling Jaya, Malaysia (3.0833° N, 101.6500° E). An optimization procedure is proposed in this study to optimize the output power P with respect to the tilt angle of the PV panel.

Generally, the total solar radiation on a tilted surface (H_T) is the sum of the beam solar radiation (H_B), diffuse radiation (H_D), and ground reflected radiation (H_R) onto the tilted surface. Thus, for a surface tilted at an angle from the horizontal, the incident total radiation is given by the relation in Equation (1):

$$H_T = H_B + H_D + H_R \quad (1)$$

The beam radiation onto the tilted surface is as expressed in Equation (2), where H_g and H_d are the monthly mean daily global and diffuse radiations on a horizontal surface.

$$H_B = (H_g - H_d) \bar{R}_b \quad (2)$$

Since Malaysia is located on the northern hemisphere, the \bar{R}_b for the surface sloped toward the equator is given by Equation (3), in which ϕ , δ , and α denote the latitude, the declination angle, and the sun hour angle for the tilted surface respectively [9].

$$\bar{R}_b = \frac{\cos(\phi - \theta_s) \cos \delta \sin \alpha + (\pi/180) \alpha \sin(\phi - \theta_s) \sin \delta}{\cos \phi \cos \delta \sin \alpha + (\pi/180) \alpha \sin \phi \sin \delta} \quad (3)$$

The sky-diffuse radiation can be calculated using Equation (4):

$$H_D = R_d H_d \quad (4)$$

where according to [10], the calculation of R_d is as shown in Equation (5).

$$R_d = (1 - \theta_s) / 180 \quad (5)$$

Thus, the total solar radiation on a tilted surface is as shown in Equation (6), where ρ refers to the ground albedo [9].

$$H_T = (H_g - H_d) \bar{R}_b + H_g \rho \frac{1 - \cos \theta_s}{2} + H_d R_d \quad (6)$$

From this, the total solar radiation falling on tilted surface is computed by varying tilt angle (θ_s) from 0° to 90° . The optimum tilt angle is taken at which solar radiation on the tilted surface H_T becomes maximum. In this research, the adjusting steps of the tilt angle is described below in Equation (7), where k refers to the iteration index and $\mu(k)$ denotes the step size of position angle increment or decrement at k .

$$\theta_s(k+1) = \theta_s(k) + \mu(k) \frac{\partial P(k)}{\partial \theta_s(k)} \quad (7)$$

It is known from [11] that the output power, P of the PV panel is directly proportional to the intensity of the solar radiation (H_T), given by Equation (8), where A refers to the surface area of the PV panel.

$$P = H_T A \tag{8}$$

Since the beam solar radiation is the main component in the incident total radiation, the intensity of solar radiation can be expressed as Equation (9) [12] where H_n is the maximum solar radiation intensity possible, and θ_I is the angle between the normal to the panel surface and the sun's rays.

$$H_T = H_n \cos(\theta_I) \tag{9}$$

It can be observed from Figure 1 that at any point in time, Equation (10) exists.

$$\theta_I + \alpha + \theta_S = 90^\circ \tag{10}$$

When the PV panel is tracking the sun, $\theta_I = 0$, and correspondingly, $\alpha + \theta_S = 90^\circ$. From Equations (8), (9), and (10), we know that

$$P = H_n A * \cos(\theta_I) = H_n A * \sin(\theta_\gamma) \tag{11}$$

where $\theta_\gamma = \alpha + \theta_S$. According to Al-Mohamad (2004), the corresponding solar radiation intensity H_n in Equation (9), for a particular solar hour angle α , can be calculated from Equation (12) where α refers to the elevation angle of the sun which is varying.

$$H_n = B * \exp[- C / \sin(\alpha)] \tag{12}$$

B and C are site- and climate-related constants and are calculated by Equation (13) and Equation (14) using data available from the meteorological department and the global constant's tables published by ASHRAE [13], where N is the day of the year and F_c is the cloudiness coefficient.

$$B = 0.132 + 0.023 \cos(F_c N) \tag{13}$$

$$C = 0.047 + 0.03 \cos(F_c N) \tag{14}$$

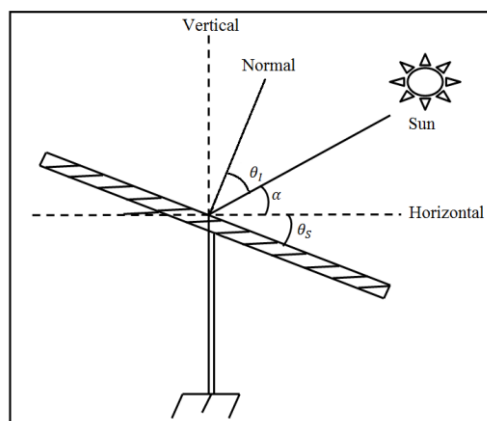


Figure 1. Illustration of angles definition

3. ELECTROMAGNETISM-LIKE MECHANISM ALGORITHM

There is a rich literature on the implementation of artificial intelligent algorithms and global optimization techniques in solar energy harvesting systems. Optimization algorithms are generally developed with the aim to search for the global optima parameter that yields the best optima values in a particular optimization problem. The Electromagnetic-like Mechanism (EM) algorithm is a population based global optimization search mechanism proposed by Birbil and Fang [14]. Guided by the electromagnetism theory, the EM imitates the attraction and repulsion mechanisms of electromagnetic charges in search for the global

optimal solution in bounded variables. In the algorithm, each of the charged particles in play is tabulated in the possible solution range. The charge magnitude of each particle relates to the objective function value. Particles with better objective yields will apply attracting forces while particles with worse objective values will apply repulsion forces onto other particles [15]. Bigger difference in objective values generates higher magnitude of attraction or repulsion force between the particles. The particles are then moved based on superposition theorem. In this research, the EM is applied to maximize the output power P generated with respect to the tilt angle, θ_s . Figure 2 shows an example of the total force, F_a applied on Q_a by the repulsive force from Q_b and attractive force from Q_c .

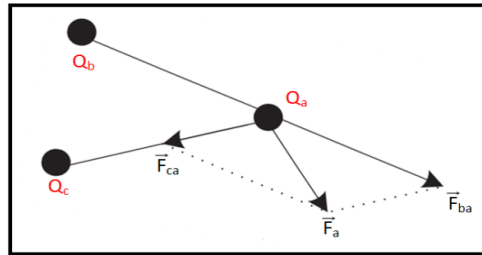


Figure 2. Total force exerted on Q_a by Q_b and Q_c

3.1. Conventional EM

The general flow of a conventional EM is as shown in Table 1. There are five major steps in the EM, namely initialization, local search, charge calculation, force calculation, and particles displacements.

Table 1. General EM Flow

Algorithm 1: EM (m , MAXITER, LSITER, δ)	
m	= number of initial particles
MAXITER	: maximum number of iterations
LSITER	: maximum number of local search iterations
δ	: local search parameter, $\delta \in (0,1)$
1:	Initialize ()
2:	iteration 1
3:	while iteration < MAXITER do
4:	Local (LSITER, δ)
5:	$F \leftarrow CalcF ()$
6:	Move (F)
7:	iteration \leftarrow iteration + 1
8:	end while

3.2. Initialization

In the initialization stage of EM, the feasible ranges of all the tuning parameters (upper bound, u_k and lower bound, l_k) are defined. Then, a number of initial particles (m) are randomly sampled from the feasible solution dimensions, each are taken as an N dimensional hyper-solid. Each value of a dimension in a particle is assumed to be uniformly distributed inside the upper and lower bound [16]. In this research, the tilt angle is set to be the tuning parameter which varies in the range of 0° to 90° . Thus, l_k is set to be 0 while u_k is set to be 90. The particles are to be evaluated with Equation (11). The particle with the largest objective value is marked as the best particle as this is a maximization problem.

3.3. Local Search

In this stage, the particles gather local information in the neighborhood and make comparisons. The original local search procedure of a conventional EM uses a line search with random search step sizes within the feasible range of a solution. This simple line search performed by tuning a particle along its dimensions one after another, restricted by a maximum and minimum feasible random step length of $\lambda \in (0,1)$ [17]. A new random step size is generated for every new iteration. In a conventional EM, this loop is immediately exited upon hitting any better objective value.

3.4. Charge Calculation

In this stage, the charge of each and every particle is calculated. This will then follow by the force calculation, in which a total force vector exerted onto a particle is obtained using the Coulomb’s Law (Lee et al. 2012). The charge of each particle is heavily dependent on its current objective value compared to the best solution found. A particle will determine if it exerts attraction or repulsion force onto another particle when the values of the two charges are compared. The calculation of the charge (q^i) is shown in Equation (15)

$$q^i = \exp\left(-n \frac{f(x^i) - f(x^{best})}{\sum_{k=1}^m (f(x^k) - f(x^{best}))}\right), \forall i \tag{15}$$

where n refers to the number of dimensions in the particle and m represents the size of the population. $f(x^{best})$ denotes the best objective value obtained so far.

3.5. Force Calculation

The forces generated by one particle onto another can be computed based on the calculated charges of each particle. A particle with a relatively better objective value will exert attraction force onto another particle while the particle with worse objective value will repulse the other particle. Based on the electromagnetic theory, the force of one particle onto another is inversely proportional to the square of the distance between the two particles and directly proportional to the product of their charges [18]. The total force vector for a particle can be determined by condensing the collective forces generated using Equation (16).

$$F^i = \sum_{j \neq i}^m \left\{ \begin{array}{l} (x^j - x^i) \frac{q^i q^j}{\|x^j - x^i\|^2} \quad \text{if } f(x^j) < f(x^i) \\ (x^i - x^j) \frac{q^i q^j}{\|x^j - x^i\|^2} \quad \text{if } f(x^j) \geq f(x^i) \end{array} \right\}, \forall i \tag{16}$$

where $f(x^j) < f(x^i)$ denotes attraction and $f(x^j) \geq f(x^i)$ refers to repulsion.

3.6. Particle Movement

In this stage, all the particles but the best are mobilized to a new location in the feasible solution space. This step is crucial to ensure a global exploration of all possible solutions. The the movement of a particle is calculated based on Equation (17), where λ denotes the global particle movement step length. In this research, it is set to be a random value between 0 and 1, assumed to be uniformly distributed between the upper boundary ($u_k = 90^\circ$) and the lower boundary ($l_k = 0^\circ$).

$$\begin{array}{ll} x_k^i \leftarrow x_k^i + \lambda F_k^i (u_k - x_k^i) & ; F_k^i \geq 0 \\ x_k^i \leftarrow x_k^i + \lambda F_k^i (x_k^i - l_k) & ; F_k^i < 0 \end{array} \tag{17}$$

Holding the absolute power of attraction towards all other particles, the best particle does not displace [19]. After a pre-determined number of iterations, the best tilt angle found by the EM is then fed into the actuator control to tilt the solar panel accordingly.

3.7. The modified EM

The setting of the search step sizes is crucial in an optimization algorithm as it determines the solutions diversification, exploitation performance and overall convergence process of an algorithm [20]. In order to better study the impact of different step size settings onto the convergence performance of the EM, the proposed EMs used in this experiment are also modified into two variants. These variants are set to operate with local search step size settings in two different extremes. EM with Larger Search Steps (EMLSS) is modified to search locally in a fixed search step of 0.1, while EM with Smaller Search Steps (EMSSS) is set to conduct its local search with a fixed search step of 0.0001.

4. RESULTS AND ANALYSIS

The results of the tilt angle optimization using the Ems are shown in this section. The results are given for the experimental PV system with the maximum output power of 210 Watts installed at the coordinates 3.0833° N, 101.6500° E. In order to demonstrate the impact of the solar tracking system in the overall power harvesting, the results are compared to that of the same system setup without any solar tracking system. A performance comparison with the conventional EM is included to investigate the improvements made by the modifications to the algorithm.

Table 2 shows the results comparison of the output power produced by different methods. The value of N is set to 100 due to the fact that the peninsular of Malaysia has the maximum solar ray around March to April every year. The cloudiness coefficient (F_c) is set at 0.98. It can be observed from Table 2 that the maximum power generated by all optimization techniques is at 1200H to 1300H. The results also show that the output power generated by EMLSS are generally less accurate compared to all the other search mechanisms. Inaccurate tilt angles are kept as best solutions in EMLSS because the large search steps employed in the algorithm skipped some other better possible solutions. EMSSS, on the other hand, returned outcomes which generates higher output power compared to EMLSS. Its small search steps enabled it to better search the tile angle with higher accuracies. The solutions obtained by EMSSS are very competitive with that of the standard EM. Figure 3 gives a better illustration on the comparison of the power generated by each optimization technique in the form of a graph. Notice that the graph line generated by EMSSS is at the top of all other techniques, indicating that it generates the most power in most of the hourly comparisons.

Table 2. Power Generation by Different Optimization Techniques ($N=100$)

	EM	EMLSS	EMSSS	Fixed PV
0700H	13.50W	11.03W	17.62W	3.18W
0800H	41.84W	32.17W	39.63W	13.55W
0900H	90.47W	87.62W	90.15W	50.78W
1000H	133.06W	128.30W	142.99W	98.83W
1100H	195.63W	190.07W	192.52W	158.36W
1200H	203.26W	202.92W	204.15W	200.98W
1300H	199.04W	199.60W	201.90W	186.86W
1400H	198.69W	195.34W	196.02W	163.10W
1500H	180.36W	178.67W	183.10W	105.04W
1600H	141.92W	135.63W	139.88W	61.77W
1700H	101.57W	90.14W	99.73W	29.86W
1800H	52.16W	41.96W	73.55W	12.55W
1900H	15.30W	12.33W	12.97W	5.13W



Figure 3. Hourly performance comparison of the EM variants.

Figure 4 shows the corresponding hourly tilt angles calculated by all the optimization techniques used in this experiment. Over-and under-compensations can be observed in the comparison of all the corresponding tilt angles, which in turn results in less power generated than the best optimum point.

Figure 5 shows the convergence curves of all the search techniques in 1200H. It can be observed from the curves that EMLSS converges rapidly and reaches near optimal tilt angle in relatively earlier iterations. However, the maximum objective value returned by EMLSS is comparatively low, which indicates that the output power generated by EMLSS is relatively less than other techniques. EMSSS search in details from the beginning of the iterations. This enabled the algorithm to search deeper for a more fine-tuned tilt angle. However, it is clearly shown in Figure 5 that the convergence rate of EMSSS is much slower compared to all other benchmark techniques.

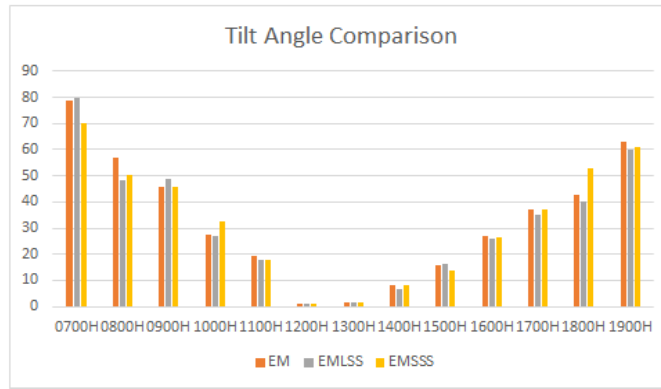


Figure 4. Comparison on the hourly tilt angles returned by the conventional EM, EMLSS, and EMSSS

Some convergence processes are sampled and analyzed. The convergence performance comparison in Figure 5 shows that EMLSS progressed very rapidly in early stages and found near-optimal values in relatively earlier iteration than all other optimization techniques. However, it is found that the near optimum results are less accurate compared to that of the conventional EM and EMSSS. EMSSS, on the other hand, converge slowly but steadily towards the optimal tilt angle search. The generated power returned by the EMSSS is relatively higher than the EMLSS, indicating that the EMSSS has the ability to hit solutions with higher accuracies.

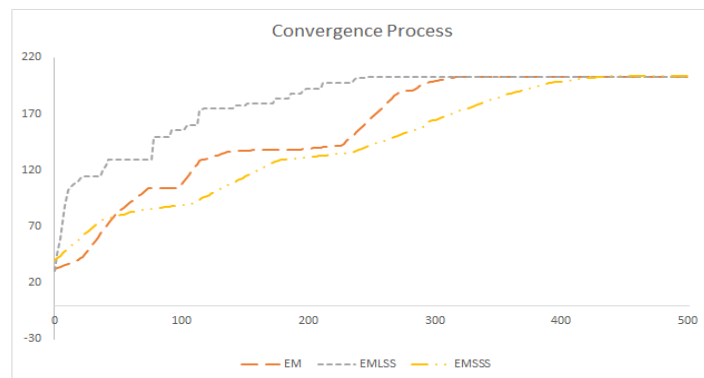


Figure 5. Convergence process of all techniques in 1200H

5. CONCLUSION

This paper proposes a new artificial intelligent approach to optimize the tilt angle of a solar tracking system using EM. In order to investigate the effect of search step size settings on the accuracy and overall performance of the algorithm, the EM is modified into EMLSS and EMSSS. The experimental results indicate that the proposed procedure performed well in searching for the best optimum tilt angles. EMSSS outperformed other variants in terms of accuracy and overall convergence performance, which in turn generates higher output energy. We thus conclude that the propose method works well in optimizing the tilt angle of a solar tracking system. Application of the EM in maximum power point tracking (MPPT) will be considered in the future work.

ACKNOWLEDGEMENTS

The authors express great acknowledgement to Universiti Tenaga Nasional (UNITEN), Malaysia for the support of this research under the BOLD scheme.

REFERENCES

- [1] Hoffert MI, Caldeira K, Benford G, Criswell DR, Green C, Herzog H. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science*. 2002: 298: 981–987.
- [2] Gholamalizadeh E, Kim MH. Thermo-economic triple-objective optimization of a solar chimney power plant using genetic algorithms. *Energy*. 2014: 70: 204–211.
- [3] Pathak M.J.M., Sanders P.G., Pearce J.M. Optimizing limited solar roof access by exergy analysis of solar thermal, photovoltaic, and hybrid photovoltaic thermal systems. *Applied Energy*. 2014: 120: 115–124.
- [4] Bakirci K. Models of solar radiation with hours of bright sun shine: a review. *Renewable and Sustainable Energy Reviews*. 2014: 13: 2580–2588.
- [5] Chandel SS, Aggarwal RK. Estimation of hourly solar radiation on horizontal surfaces in Western Himalayas. *Smart Grid and Renewable Energy*. 2011: 2: 45–55.
- [6] Chandel SS, Aggarwal RK, Pandey AN. New correlation to estimate global solar radiation on horizontal surfaces using sunshine hour and temperature data for Indian sites. *Journal of Solar Energy Engineering*. 2005: 127 (3): 417–20.
- [7] El-Sebaï AA, Al-Hazmi FS, Al-Ghamdi AA, Yaghmour SJ. Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. *Applied Energy*. 2010: 87: 568–76.
- [8] Demain C, Journée M, Bertrand C. Evaluation of different models to estimate the global solar radiation on inclined surfaces. *Renewable Energy*. 2013: 50: 710–21.
- [9] Yadav AK, Chandel SS () Tilt angle optimization to maximize incident solar radiation: A review. *Renewable and Sustainable Energy Reviews*. 2013: 23: 503–513.
- [10] Tian YQ, Davies-Colley RJ, Gong P, Thorrold BW. Estimating solar radiation on slopes of arbitrary aspect. *Agricultural and Forest Meteorology*. 2001: 109: 67–77.
- [11] Ranganathan R, Mikhael W, Kutkut N, Batarseh I. Adaptive sun tracking algorithm for incident energy maximization and efficiency improvement of PV panels. *Renewable Energy*. 2001: 36: 2623–2626
- [12] Kacira M, Simsek M, Babur Y, Demirkol S. Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey. *Renewable Energy*. 2004: 29: 1265–1275.
- [13] ASHRAE 2011 Handbook - Heating, ventilating, and air-conditioning applications. American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. USA.
- [14] Birbil SI, Fang SC () Electromagnetism-like mechanism for global optimization. *Journal of Global Optimization*. 2003: 25: 263–282.
- [15] Wu PT, Hung YY, Lin ZP. Intelligent forecasting system based on integration of electromagnetism-like mechanism and fuzzy neural network. *Expert Systems with Applications*. 2014: 41: 2660–2677.
- [16] Dutta R, Ganguli R, Mani V. Exploring isospectral cantilever beams using electromagnetism inspired optimization technique. *Swarm and Evolutionary Computation*. 2013: 9: 37–46.
- [17] Zhang CJ, Li XY, Gao L, Wu Q. An improved electromagnetism-like mechanism algorithm for constrained optimization. *Expert Systems with Applications*. 2013: 40: 5621–5634.
- [18] Lee CH, Lee YC () Nonlinear systems design by a novel fuzzy neural system via hybridization of electromagnetism-like mechanism and particle swarm optimization algorithms. *Information Sciences*. 2012: 186: 59–72.
- [19] Cuevas E, Oliva D, Zaldivar D, Pérez-Cisneros M, Sossa H. Circle detection using electro-magnetism optimization. *Information Sciences*. 2012: 182: 40–55.
- [20] Ratnaweera A, Halgamuge S, Watson HC. Self-organizing hierarchical particle swarm optimizer with time-varying acceleration coefficients. *IEEE Trans. Evol. Comput.* 2004: 8: 240–255.