Journal of Operation and Automation in Power Engineering

vol. 12, no. 4, Dec. 2024, Pages: 312-325

http://joape.uma.ac.ir

Virtual Power Plant Operation Using an Improved Meta-heuristic Optimization Algorithm Considering Uncertainties

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Abstract— *In this paper, virtual power plant (VPP) planning is done using distributed generation sources to create a safe platform for electricity exchange and to increase the profitability and sustainability of electricity. In the proposed model, the effect of micro-grid interaction with the electricity market in the presence of distributed generation resources and storage is investigated. To solve this problem, an improved artificial bee colony algorithm using the accept-reject method (AR-ABC) is used. The AR method is employed to limit the initial search space as well as for the scenario reduction process. Also, uncertainties related to loads and renewable sources are formulated in a sample micro-grid including micro-turbine (MT), fuel cell (FC), wind turbine (WT), photovoltaic cells (PV) and batteries for storage; the results are compared with those of other methods, which shows this method works better than others. The software simulations of this research are done in the MATLAB software environment.*

Keywords—Accept-reject method, Electricity market, Renewable energy sources, Uncertainty, Virtual power plant.

NOMENCLATURE

Variables

αP	Temperature coefficient
α , ω	Parameters of the beta PDF
β	Weight factor related to the step of movement
ΔP	The difference between the original losses and the new losses of feeders
$\mathrm{Xi,j}$	Updated position of *i* th particle
τ	Numerical value related to the algorithm stop criterion
$\upsilon_{\mathrm{i,j}}$	Updated velocity vector of *i* th particle
I_i	The original flow of the i^{th} branch
$P_{Sj}(t)$	Output active power of *j* th storage at time *t*
R_i	The resistance of the i^{th} branch
v	Wind speed [m/s]
$\mathrm{C}_{\Delta \mathrm{P}}$	The cost of the ΔP
$\mathrm{df}^{\mathrm{PV}}$	Derating factor
$\mathrm{S_{i,STC}}$	Solar irradiance at standard test conditions
$\mathrm{S_i(t,s)}$	Solar irradiance for the PV array at time t and scenarios
$\mathrm{T_{c,STC}}$	Temperature of PV cell under standard conditions
$\mathrm{T_c}$	Temperature of PV cell
$\mathrm{x_j^{min}}$, $\mathrm{x_j^{max}}$	Lower and Upper bounds of the *j* th
k, c	Shape and scale parameters of Weibull PDF
$\mathrm{P_r^{wt}}\nu_{\mathrm{r}}$	Output power and rated speed for WT
ν_{ci} , ν_{co}	Cut in and cut out speed states of WT
δ	Movement step index
C_{FC}	Proposed cost for FC
C_{Grid}	Bid price of electricity
C_j	Suggested cost for storage devices
C_{MT}	Proposed cost for MT
C_{PV}	Proposed cost for PV system
C_{WT}	Proposed cost for WT
N_g	Total number of production units
N_s	Total number of storage units
$P_{Battery}$	Power generated by battery
P_{FC}	Power generated by fuel sell
P_{Grid}	Power bought or sold from the market
P_{MT}	Power generated by MT
P_{PV}	Power generated by PV system
P_{WT}	Power generated by WT
PV^{array}	Nominal PV capacity for array
S_{Gi}	Unit start-up cost
S_{Sj}	Unit shutdown cost
U_{FC}	Indicating whether the FC is OFF or ON
U_j	Indicating whether the storage devices is OFF or ON
U_{MT}	Indicating whether the MT is OFF or ON
U_{PV}	Indicating whether the PV system is OFF or ON
U_{WT}	Indicating whether the WT is OFF or ON

Received: 05 Sept. 2022
Revised: 18 Dec. 2022
Accepted: 02 Jan. 2023
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DOI: 10.22098/joape.2023.11310.1844
Research Paper

1. INTRODUCTION

Today, due to the use of fossil fuels for generating electricity in power plants, the emission of industrial pollutants is one of the most fundamental issues in power systems. Distributed energy resources (DERs) that are close to load centers are used to reduce the losses of electrical power and environmental pollutants. The VPP is planned to reduce the complexities and problems associated with the control and planning of DERs. The duty of the VPP is to manage the large number of DERs scattered throughout the system. One of the problems with VPPs is the uncertainty of renewable energy sources such as wind and solar in PV and WT [1]. Therefore, these uncertainties must be modelled and formulated in the optimization problem. In this paper, a sample network is planned by the VPP to reduce the generation and operation costs and increase profit. DGs work together to supply network loads, and store and sell electricity when the price of electricity in the grid is high and buy electricity when the price of electricity is cheap.

There are many types of research in the field of VPP planning, including as follows: In [2], peer-to-peer VPPs were analyzed and evaluated. On a small scale, peer-to-peer operating systems for VPP were introduced for coordination between manufacturers and consumers. The authors in [3] proposed a VPP planning model which used renewable energy sources and storage units to participate in the energy market. A two-stage stochastic planning problem, as well as a short-term and long-term strategy for solving the problems related to the uncertainty of renewable energy sources, were presented. In [4], in order to increase the profit and the network reliability under maximum load conditions, a new strategy was proposed for the simultaneous use of the load response program with electric vehicles in the parking lots. This strategy was used for the energy management of industrial VPPs in the short-term planning of DERs. The simulation results proved that the presence of EV in the EV parking area reduced the utilization of the full capacity of the power grid. In [5], the planning of a VPP was done in several layers. In this research, a randomized model with a machine learning randomized control scheme was used to address the uncertainties in VPP. The simulation results proved that the effect of this planning in terms of penalty reduction in most cases was better than that of the definitive approach. In [6], considering the issues related to the stability of electrical energy in municipal electricity, expressing the concept of VPP could address this concept for urban sustainability by using the control and stability issues and communication technologies and removing the existing limitations and expressing future solutions and plans. In [7], for a smart grid, an efficient three-level distribution model was proposed to determine the optimal bilateral transactions, which aimed to minimize production costs and transmission costs. The performance of this load distribution model was tested on the modified IEEE-14 bus system and the modified IEEE-30 bus system. In [8], a study was performed on a VPP with electric heating in Tianjin, China. In this research, first, the mechanism and structure of the VPP market were studied and, then, a model was considered for investigating the penalty for wind uncertainty. The results showed that the two-stage optimization model performed well, increased system reliability and reduced costs. In [9], a two-layer power management model for a smart distribution network was considered, and the first and second layers were examined to maximize profits and reduce losses and voltage fluctuations, respectively. The proposed model was implemented by the Benders decomposition method in a standard IEEE 69 bus distribution network. In [10], a VPP was considered as an example for solving the problems related to the parameters' uncertainties that were generated or demanded randomly, such as wind speed, electricity prices and load demand. To this end, a strategy based on a deep learning approach with two-way short-term memory networks (BLSTM) was proposed. In [11], optimization algorithms based on the Big Bang algorithm were used to increase electricity trade in unbalanced distribution networks, which aimed to manage electrical energy in unbalanced distribution networks to reduce energy costs. This method was done through optimal planning of renewable resources, optimal load planning and optimal use of energy storage in the network. In order to reduce the total cost of cargo supply and decrease voltage fluctuations, a load response program was proposed for the simultaneous use of electric vehicles. In [12], for the robust self-scheduling of VPP, a new method based on information gap decision theory (IGDT) was used for electricity markets. For exchange in the pool market, the price of energy was uncertain, but the decision variables in this research were energy. Researchers of this research defined self-scheduling by considering the level of risk-taking. In [13], to solve the problem of VPP uncertainty and make VPP planning easier, information gap theory was used and the two-stage planning method of power plants was employed to determine the effectiveness of VPP planning; the conditions for the load response program were implemented in the IEEE 24-bus network. The results obtained in two cases were examined and compared with each other.

In this paper, the planning of a VPP for supplying the electricity consumption of a micro-grid that participates in the electricity market and exchanges power with that is examined. To solve the problem, the new AR-ABC algorithm is used, which improves the numerical optimization process. The micro-grid is programmed to be able to sell electrical power to the electricity market in the hours that electricity prices are high in the market. Also, when the price of electricity in the market is low, the micro-grid is programmed to buy electricity from the market. A new method for modelling the uncertainty of load, WT and PV system, considering the probabilistic functions related to each of these unstable sources, as well as the scenario reduction process is implemented using the AR method. In order to examine the effect of power exchange with the electricity market and examine the effectiveness of the AR-ABC algorithm, three types of case studies, each of which has ten different scenarios, are examined, so that we can check the behavior of VPP according to the limitations of the electricity market. According to Table 1, the problem-solving method and other VPP operation parameters are compared in this paper with other recent methods.

Other parts of this article are as follows: ABC and AR methods are described. In the third section, the proposed method is fully investigated and, in the fourth section, the planning of a VPP is solved using the proposed method. In the fifth section, the simulation results are presented and analyzed; finally, the general result of this research is stated in the last section.

2. Problem-solving Process

2.1. Accept-Reject Method

In particular, the AR method can be called a specific sequence of a set of identically distributed independent random variables [18, 19]. In this method, to create one or more random variables, first, another random variable that is easier to produce must be created. Finally, the amount produced is accepted or rejected by performing an experiment or a condition [20]. The distribution of the accepted point will be the same as the distribution of the random variable. If we generate a random value with density $f(x)$, we use it to generate a density function $g(x)$ that has the same distribution as $f(x)$. If c is the maximum $\frac{g(x)}{f(x)}$, for the density of $g(x)$, we act as in Figure 1 [21] and Figure 2 shows which points in the function $f(x)$ are accepted or rejected by the AR method.

2.2. ABC Algorithm

Inspired by the collective behavior of bees to find the best place (in terms of nectar in that place), this algorithm was first proposed by Karaboga [22]. This collective behavior consists of four phases. In the first phase, which is the initial search phase, the bees randomly go to food sources to find nectar [23], which is formulated as Equation (1):

$$x_{i,j} = x_j^{min} + rand(0,1) \times (x_j^{max} - x_j^{min}) \tag{1}$$

In the second phase, which is the employed bee phase, the resources in the vicinity of the previous sources are randomly searched and formulated as Equation (2) [23]:

$$\upsilon_{i,j} = x_{i,j} + \phi_{i,j}\,(x_{i,j} - x_{k,j}) \tag{2}$$

$\upsilon_{\mathrm{i,j}}$ is the velocity vector to update the position of the bees and $\phi_{\mathrm{i,j}}$ is a uniform random number in [1 1]. In the third phase, the onlooker bees only decide on better solutions. So, they work on solutions that have higher probability of finding nectar [24] as formulated by Equations (3) and (4):

$$\begin{cases} \frac{1}{1+f(x_i)} & f(x_i) \geq 0 \\ |1+f(x_i)| & f(x_i) < 0 \end{cases} \tag{3}$$

Table 1. Literature works related to VPP management

Reference No.	Problem solving method	Objective function	Modified or new algorithm	Uncertainties	Formulation type		Limitations		Sources		
					Stochastic	Deterministic	power generation	Market	Renewable	Nonrenewable	Energy storage system
[2]	Two-stage random game algorithm	Risk management - reducing energy consumption	×	✓	✓	×	✓	✓	✓	✓	✓
[4]	Complex number nonlinear programming	Increase profit - decrease operating cost	×	×	✓	×	✓	✓	✓	✓	✓
[8]	Non-dominant Classified Genetic Algorithm	Increasing the profit of the virtual power plant	×	×	✓	×	✓	✓	✓	✓	✓
[9]	Benders analysis method	Increasing profits - reducing network costs	×	✓	✓	×	✓	✓	✓	×	×
[10]	Deep learning based on short-term memory networks	Increasing the profit of the virtual power plant	×	✓	×	✓	✓	✓	✓	✓	✓
[14]	Column constraint generation algorithm	Reducing virtual power plant operating costs	×	✓	×	✓	✓	×	✓	✓	✓
[15]	Linear programming with robust optimization	Reduce network costs	×	✓	×	✓	✓	✓	✓	×	✓
[16]	Sequence-based differential evolution	Increase profit - Reduce network costs	✓	×	✓	×	✓	✓	✓	✓	✓
[17]	Column constraint generation algorithm	Provision of consumption load - storage management	×	×	✓	×	✓	✓	✓	✓	✓
This paper	Artificial bee colony algorithm using the accept-reject method	Increase profit - Reduce operating costs	✓	✓	✓	×	✓	✓	✓	✓	✓

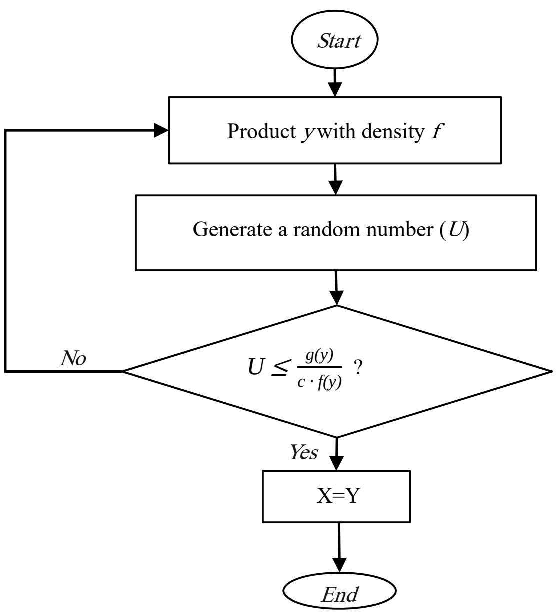

Fig. 1. Flowchart related to the acceptance or rejection process of a random point U by the accept-reject method.

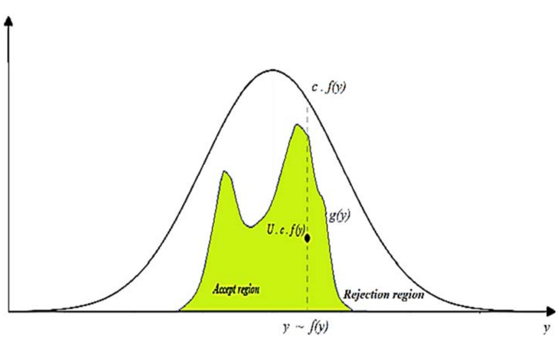

Fig. 2. Examining acceptance or rejection of the random variable u using the AR method.

$$P_i = \frac{fit(X_i)}{\sum_{i=1}^{S_N} fit(X_i)} \tag{4}$$

In the fourth stage, which is the stage of scout bees, with the help of the "limit parameter", which is displayed by symbol T_r, the food source that cannot be improved through a certain number of paths is destroyed [25]. The new situation can be easily reproduced according to Equation (1).

3. Proposed Algorithm

Considering that in the first phase of the ABC algorithm, the initial search is usually done completely randomly and sometimes this search is long, in the proposed method, the AR method is used to make the initial search smarter. The AR method is formulated in the form of Equations (5) to (7) [21, 26].

$$c_i = max\left(\frac{g_i(x)}{f(x)}\right) \tag{5}$$

$$U = rand\left\{g_i(x)\right\} \tag{6}$$

$$X_i = \begin{cases} accept & U \leq \frac{g_i(y)}{c_i \times f(y)} \\ reject & else \end{cases} \tag{7}$$

Then, due to the limited search space, access to optimal answers with high accuracy and better quality increases. We include new $x_{i,j}^{min}$ and $x_{i,j}^{max}$ in the previous equations. Equation (1) is updated as Equation (8). Also, for the controlled and optimal movement of employed bees, Equation (2) is replaced according to Equation (9) [25, 26]:

$$x_{i,j}^{new} = x_j^{min_{new}} + rand(0,1) \times (x_j^{max_{new}} - x_j^{min_{new}}) \tag{8}$$

$$v_{i,j}^{new} = x_{i,j}^{new} + \phi_{m,i} \cdot x_{k,i} \qquad k = i = 1, 2, \ldots, F_N \tag{9}$$

$$\begin{cases} x_{k,i} = \delta & x_{i,j}^{new} = 0 \\ x_{k,i} = \delta \cdot |x_{b_i}| & else \end{cases} \tag{10}$$

$$\delta = \frac{\beta}{n} \qquad n = 1, 2, \ldots, N \tag{11}$$

$$x_{b_1},\ldots,x_{b_{F_N}}\sim\ U(x_{b_{min}},x_{b_{max}}) \quad (12)$$

$$x_{b_{min}}=x_{i,j}^{new}-\frac{x_{i,j}^{new}}{2} \quad (13)$$

$$x_{b_{max}}=x_{i,j}^{new}+\frac{x_{i,j}^{new}}{2} \quad (14)$$

In (10), index β, which represents the weight coefficient of the motion stage, is inversely related to index *N*, which indicates the number of repetitions. $\phi_{m,i}$ must be chosen randomly, can be 1 or -1 and cannot be zero because, in this case, the second part of Equation (8) becomes zero and no improvement is achieved compared to the previous iteration. So, one unit is added to the trial index. The size of β for long and short steps is as Equation (15).

$$\begin{cases}\frac{x_{b_{max}}+\left|x_{b_{min}}\right|}{2}\leq\frac{x_{i,j}^{max\,new}}{3} & \beta=1\\ \frac{x_{b_{max}}+\left|x_{b_{min}}\right|}{2}>\frac{x_{i,j}^{max\,new}}{3} & \beta=10\end{cases} \quad (15)$$

The stopping criterion of the algorithm is formulated as Equation (16):

$$\begin{cases}\frac{\upsilon_{i,j}^{new}+\cdots+\upsilon_{i,j+\gamma}^{new}}{\gamma}=\upsilon_{m,i}\\ \upsilon_{i,j}^{new}-\upsilon_{i,j-1}^{new}=\tau\end{cases} \quad (16)$$

Other parameters used for the proposed algorithm are: the initial population is equal to 20 bees, the number of food sources (*SN*) is half of the initial population, the limit parameter is equal to *SN*×*D*, the number of objective function calls is 30 trials and the number of iterations is 1000. Table 2 presents the pseudo-code of the proposed algorithm.

4. VIRTUAL POWER PLANT PLANNING USING THE AR-ABC ALGORITHM

At this stage, a sample micro-grid is programmed for 24 h as an optimization problem for VPP operation and, finally, the results obtained from different aspects are examined and compared.

4.1. Virtual Power Plant

A VPP is a tool that was first introduced by Awerbuch as a "virtual tool" for controlling and planning production units [27, 28]. VPP is an integrated network, the components of which can include a variety of storage systems and power generation generators that participate in the energy markets as an integrated system. Energy management system (EMS) is one of the main components of VPP, the main task of which is to monitor and manage VPP components [6, 29]. The main purpose of this research is to participate in the energy market to increase profits and reduce losses with VPP planning.

4.2. Test System

The network studied in this paper includes residential, commercial and industrial loads. The single-line diagram of the test system and the limitations and suggestions of RES and Utility are shown in Figure 3. The real-time market prices, the predicted output power of WT and PV systems and the daily load curve of a sample micro-grid for a full day are presented in Table 3 and Figure 4 The limitations and bids of RESs and the utility are shown in Table 4 [30, 31]. The cost of starting and shutting down the MT and FC is 0.96 and 1.65 (€ct), respectively; the maintenance cost of battery, WT, PV, FC and MT is 0.38, 1.073, 2.584, 0.294 and 0.457 (€ct/KWh), respectively.

In this paper, a sample network including MT, FC, PV system, WT and energy storage is used. In order to exchange energy with the upstream grid, subject to power generation constraints, when the price of electricity is cheap, electricity is purchased from the grid; when the price of electricity is high, electricity is sold to the electricity market.

4.3. Objective Function

The objective function of this problem is defined as Equation (17) [31].

$$\sum_{t=1}^{T}Cost=\sum_{t=1}^{T}\left(\begin{array}{c}P_{Grid}(t)\cdot C_{Grid}(t)+U_{WT}(t)\cdot P_{WT}(t)\cdot C_{WT}(t)+U_{PV}(t)\\ \cdot P_{PV}(t)\cdot C_{PV}(t)+\ U_{FC}(t)\cdot P_{FC}(t)\cdot C_{FC}(t)+U_{MT}(t)\\ \cdot P_{MT}(t)\cdot C_{MT}(t)+\sum_{j=1}^{N_g}S_{Gi}\left|U_i(t)-U_i(t-1)\right|+\\ \sum_{j=1}^{N_s}\ S_{Sj}\left|U_j(t)-U_j(t-1)\right|-\Delta P(t)\cdot C_{\Delta P}(t)\end{array}\right) \quad (17)$$

$$\sum_{t=1}^{T}\Delta P(t)=\sum_{t=1}^{T}\left(P_{original\ losses}(t)-P_{new\ losses}(t)\right) \quad (18)$$

$$P_{final\ losses}(t)=\sum_{t=1}^{T}\sum_{i=1}^{N_{br}}R_i\ \times\ \left|I_i(t)\right|^2 \quad (19)$$

4.4. Constraints

There are constraints on electricity generation and consumption. For efficient optimization, these constraints must be considered. This section describes the various constraints for electrical power. The power balance constraints are obtained according to Equation (20) [31].

$$\sum_{t=1}^{T}\left(\begin{array}{c}P_{Grid}(t)+P_{WT}(t)+P_{PV}(t)+P_{FC}(t)\\ +P_{MT}(t)+P_{Battery\ discharge}(t)\end{array}\right)=\sum_{t=1}^{T}\left(P_{Load}(t)+P_{Battery\ charge}(t)+P_{Loss}(t)\right) \quad (20)$$

The FC and MT constraints are obtained according to Equations (21) to (22) [31].

$$P_{FC_{min}}(t)\leq P_{FC}(t)\leq P_{FC_{max}}(t);\quad t=1,\ldots,T \quad (21)$$

$$P_{MT_{min}}(t)\leq P_{MT}(t)\leq P_{MT_{max}}(t);\quad t=1,\ldots,T \quad (22)$$

Equation (23) is used to express the output power limits of a WT for 24 h [31].

$$P_{WT\,min}\leq P_{WT}(\mathrm{t})\leq P_{WT\,max};\quad t=1,\ldots,T \quad (23)$$

Equation (24) is used to express the limit of output power produced by PV panels for 24 h [31].

$$P_{PV\,min}(t)\leq P_{PV}(\mathrm{t})\leq P_{PV\,max}(t);\quad t=1,\ldots,T \quad (24)$$

The utility and storage constraints are obtained according to Equations (25) and (26).

$$P_{Grid_{min}}(t)\leq P_{Grid}(t)\leq P_{Grid_{max}}(t);\quad t=1,\ldots,T \quad (25)$$

Table 2. Pseud code of proposed algorithm according to the proposed problem.

Algorithm: AR-ABC
Limiting the search space by AR method (Equations (5) to (7))
Determining the upper and lower limits of the parameters
Initialization by new parameters and units (Equation (8))
Evaluate fitness value
$n = 1$
While ($n < N$)
For $n = 1 : N$
Calculate the new bee position (x_{mi}) (Equations (9) to (10))
Calculate the value of "β" and the best position of the bee and the new position of the bees (Equation (11))
Determine $x_{b_{min}}$ & $x_{b_{max}}$ for all units (Equations (13) to (14))
For all dimensions
Fitness calculations
If fitness (n)<= fitness (n-1) (Equations (15) or (16))
T_r=0
else
T_r=T_r+1
End If
End For
End For
$n = n + 1$
End While

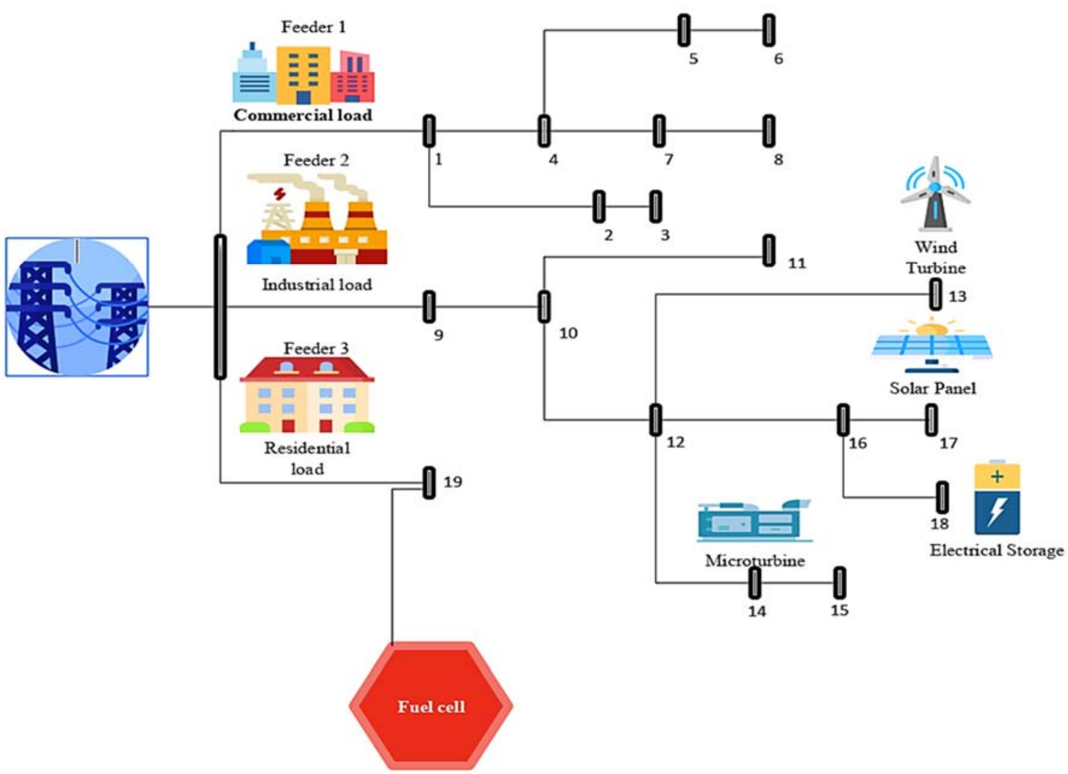

Fig. 3. Single line diagram of the test system

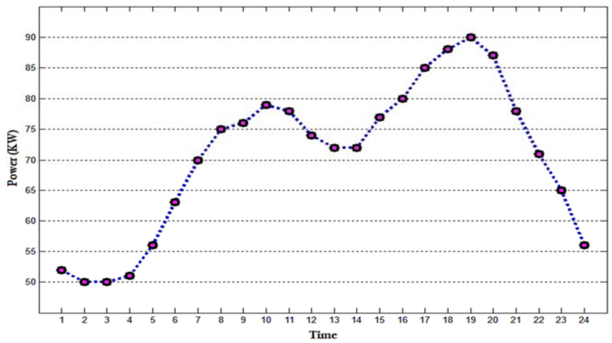

Fig. 4. Daily load curve of a typical micro-mrid.

Table 3. Real-time market prices and the forecasted output power of PV system and WT.

hour	PV	WT	Price (€ct /kWh)
1	0	1.7850	0.23
2	0	1.7850	0.19
3	0	1.7850	0.14
4	0	1.7850	0.12
5	0	1.7850	0.12
6	0	0.9150	0.20
7	0	1.7850	0.23
8	0.200	1.3050	0.38
9	3.750	1.7855	1.50
10	7.5279	3.0900	4.00
11	10.450	8.7750	4.00
12	11.964	10.413	4.00
13	23.900	3.9228	1.50
14	21.050	2.3766	4.00
15	7.875	1.7855	2.00
16	4.225	1.3050	1.95
17	0.550	1.7850	0.60
18	0	1.7850	0.41
19	0	1.3020	0.35
20	0	1.785	0.43
21	0	171.3017	1.17
22	0	1.3005	0.54
23	0	0.9150	0.30
24	0	0.6150	0.26

Table 4. The limitations and bids of RESs and the utility.

Type	Bid(€ct/KWh)	Startup/Shut down cost(€ct)	Min power (KW)	Max power (KW)
WT	1.073	0	0	15
FC	0.294	1.65	3	30
Utility	-	-	-30	30
Battery	0.38	0	-30	30
PV	2.584	0	0	25
MT	0.457	0.96	6	30

$$P_{Sj_{min}}(t) \le P_{Sj}(t) \le P_{Sj_{max}}(t)\,; \quad t = 1, \ldots, T \tag{26}$$

The battery cannot be charged and discharged at the same time. So, its limit is formulated according to Equation (27):

$$X(t) + Y(t) \le 1; \quad t = 1, \ldots, 24; \quad X \text{ and } Y \in \{0, 1\} \tag{27}$$

4.5. Uncertainty Modeling

The load, solar energy and wind speed have unknown values and cannot be expressed definitively. So in this research for investigating the uncertainty of load, sun and wind energy, the AR method is used to reduce the scenarios and deal with the probabilities of the model. In this research, 10 scenarios related to each of the wind, sun and load scenarios are extracted and examined and calculated using the AR method.

A) Wind Speed Modeling

The Weibull distribution function is used for wind speed modelling [32].

$$PDF(v) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{\left(-\left(\frac{v}{c}\right)^k\right)} \tag{28}$$

Equation (29) shows the wind turbine production power in terms of different wind speeds, which is considered a quadratic equation [33].

$$P_{WT}(v_t) = \begin{cases} 0 & 0 \le v_t \le v_{ci} \ \text{ or } \ v_t \ge v_{co} \\ P_r^{wt} \cdot \frac{v_t^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & v_{ci} \le v_t \le v_r \\ P_r^{wt} & v_r \le v_t \le v_{ci} \end{cases} \tag{29}$$

B) Solar Irradiance Modeling

The beta distribution function is used to model solar uncertainty and the solar model is in the form of Equation (30) [34].

$$PDF(S_i) = \begin{cases} \frac{\Gamma(\alpha,\omega)}{\Gamma(\alpha)\cdot\Gamma(\omega)} \cdot S_i^{(\alpha-1)} \cdot (1-S_i)^{\omega-1} \\ \quad , \ for\ 0 \le S_i \le 1,\ \alpha,\omega \ge 0 \\ 0 \quad \text{else} \end{cases} \tag{30}$$

Equation (31) is used to express the limit of output power produced by PV panels for 24 hours [35].

$$P_{pv}^{e}(S_i(t,s)) = PV^{array} df^{PV} \left(\frac{S_i(t)}{S_{i,STC}}\right) \left[1 + \alpha P\left(T_c - T_{c,STC}\right)\right] \tag{31}$$

C) Load Modeling

Load modelling is performed according to Equation (32) using the normal probability distribution function [34].

$$PDF(L) = \frac{1}{\sqrt{2\pi\sigma_L^2}}\, e^{-\frac{(L-\mu_L)^2}{2\sigma_L^2}} \tag{32}$$

Considering that the set of network loads is classified into three main groups: domestic, industrial and commercial, we assume that each of the sets of domestic, industrial and commercial loads behaves similarly. Similar behavior means that, for example, all the loads in a set are simultaneously at their maximum or all the loads in a set are at their average values at the same time. So, different modes are considered for all the three sets. Figure 5 shows a twelve-point normal distribution. Assuming that each of

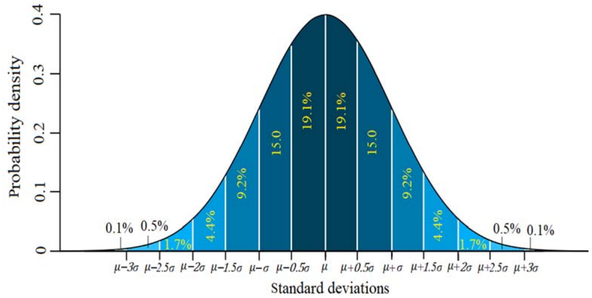

Fig. 5. Twelve-point normal distribution

these three sets has twelve modes similar to Figure 5, the total number of possible scenarios will be equal to $12^3 = 1728$. By considering each of the different states for multiple times, the possible scenarios under these assumptions will be in the form of Table 5. In this table, the total load in each case is the sum of household, industrial and commercial loads, which shows a possible scenario.

Investigating all the possible scenarios requires a large amount of time and energy. In order to be able to quickly identify the effective scenarios and use them to comment on the operation of the VPP, the AR method is used to reduce the scenario. The normal distribution function which is introduced in Equations (30) is used as $g(x)$ in Equations (5) to (7) and sampling of this function according to Equations (5) to (7) of Figures 1 and 2 is done. Thus, $g(x)$ is introduced as Equation (33) and should be sampled from it:

$$g(x) = \frac{1}{\sqrt{2\pi\sigma_L^2}}\ e^{-\frac{(L-\mu_L)^2}{2\sigma_L^2}} \tag{33}$$

To obtain the value of c, the largest number must be obtained from the result of the equation $\left(\frac{g(x)}{f(x)}\right)$. Now, by testing the condition of $U \leq \frac{g_i(y)}{c_i \times f(y)}$, according to Equation (7), if the random value of U meets the requirement, that value is accepted; otherwise, it is rejected. This process continues until the desired number of scenarios is set. According to the previous explanation, Figure 6 shows an example of using the AR method to reduce the scenario; out of 1728 possible scenarios, more than 99% are rejected. Since the number of possible scenarios is very large, the samples that are the most effective ones are extracted through the AR method. Random variable U should be chosen to have distribution $g(x)$. Also, $f(x)$ can be a uniform distribution function or a normal distribution function. $f(x)$ is actually the entire search space or all the available scenarios.

Figure 7 presents the structured flowchart of the proposed algorithm according to the proposed problem.

4.6. Case Studies and Basic Information

To analyze and use distributed generation resources for optimal network performance and evaluate the impact of distributed generation sources to increase profits and reduce costs, the issue is investigated in three different situations. The explanations provided below describe several case studies for this study:

(**Case 1**): DGs can generate electricity within their allowable range. The possibility of exchanging electricity with the market is allowed only in the range and is limited.

(**Case 2**): DGs can be turned on or off, but the initial charge of the battery is zero. This means that due to the battery charge, the amount of battery discharge in the early hours is limited. PV and wind power must be fully in the circuit. The possibility of exchanging electricity with the market is allowed only in the range and is limited.

(**Case 3**): DGs can only generate electricity within their allowable range and the possibility of exchanging electricity with the main network is unlimited.

Also, Table 6 introduces the parameters used for implementing the problem simulation [35].

5. Simulations and Discussion

In order to investigate the performance of the network and evaluate the impact of distributed generation resources on increasing profits and reducing costs, the issue is examined in three different situations.

5.1. Results of the First Case Study

According to Figure 8, the cost of VPP for the first case study is compared with the cost obtained by other algorithms. According to the obtained results, the AR-ABC algorithm imposes the lowest cost on the studied system; according to Figure 9 and Table 7, for the first case study, it is as follows:

- From 1 to 7 am: Due to the absence of sunlight, electricity is not produced by PV and, due to the cheap price of electricity in the electricity market, the maximum possible power is purchased from the grid, which makes MT, the cost of which is higher than Utility for producing power with its minimum power. FC produces power at its maximum capacity because it is economical. Excess production is used for storage for batteries.
- At 8 am: It is the same as 7 am, with the difference that PV generation helps to generate grid power.
- From 9:00 to 17:00: Due to the increase in the price of electricity in the electricity market, in order to gain profit from the electricity market, all units are requested to produce electricity to supply electricity to the main grid in addition to it. To supply the requested load and sell it in the electricity market, the battery injects its stored power into the grid according to the required power. Since FC and MT are economical, they generate power at their maximum capacity. WT and PV work together with other units and generate electricity. All the excess power of the micro-grid is injected into the main grid to be sold in the electricity market.
- From 18:00 to 20:00: The price of electricity is slightly cheap; so, power is received from the grid, which makes MT, the cost of which is higher than Utility to produce power with its minimum power. FC produces power at its maximum capacity. The load demand is slightly high; so, the battery is discharging.
- From 21 to 22: The same as 8 am, but during this hour, electricity is not produced by PV and the power demand is more.
- From 23 to 24: Electricity is not produced by PV. The maximum possible power is purchased from the grid, so MT production is minimized because its cost is higher than the Utility. FC produces power at its maximum capacity because it is economical. Excess production is used for storage for batteries. Figure 10 shows the graph of the total cost function related to the first case study.

5.2. Results of the Second Case Study

According to Figure 11, the cost of VPP for the second case study is compared with the cost obtained by other algorithms. According to the obtained results, the AR-ABC algorithm imposes the lowest cost on the studied system; according to Figure 12 and Table 8, for the second case study, it is as follows:

- From 1 to 7 am: Due to the absence of sunlight, electricity is not produced by PV; due to the cheap price of electricity in the electricity market, the maximum possible power is purchased from the grid, but because the battery must be fully charged in the early hours, it makes high power MT

Table 5. The created scenarios

Scenario Number	Residential Load	Commercial Load	Industrial Load	Total Load	Possibility
1	$P_{Residential\ 1}$	$P_{Commercial\ 1}$	$P_{Industrial\ 1}$	$P_{t\ 1}$	0.125e-6
2	$P_{Residential\ 2}$	$P_{Commercial\ 2}$	$P_{Industrial\ 2}$	$P_{t\ 2}$	0.425e-6
...	...	...	...	...	...
1728	$P_{Residential\ 1728}$	$P_{Commercial\ 1728}$	$P_{Industrial\ 1728}$	$P_{t\ 1728}$	0.125e-6

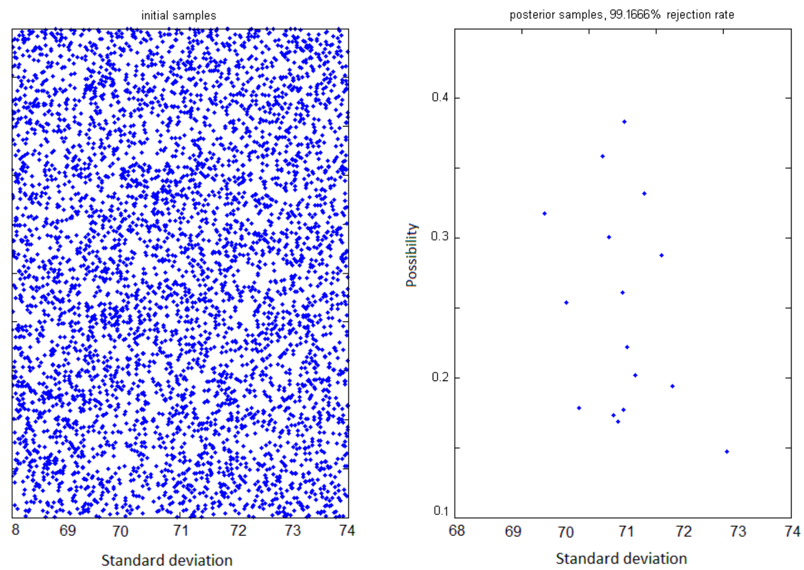

Fig. 6. An example of using the AR method to reduce the load scenario at 22:00.

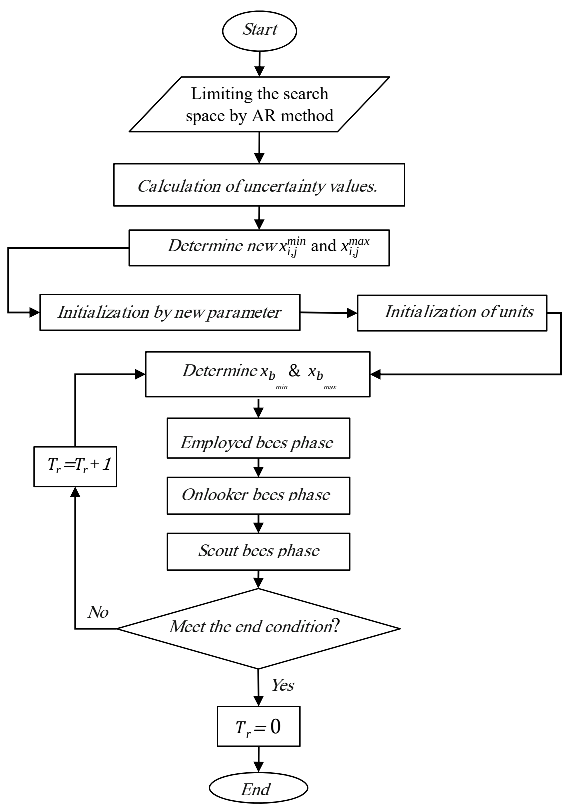

Fig. 7. Flowchart of the AR-ABC algorithm according to the proposed problem

Table 6. Parameters used in the simulation

Parameter	Unit	Value
P_r^{wt}	kW	15
v_{ci}	m/s	4
v_r	m/s	10
v_{co}	m/s	22
T_{mc}	$^{\circ}C$	60
$T_{c,STC}$	$^{\circ}C$	25
df^{PV}	$\%$	80
αP	$\%/^{\circ}C$	-0.5
$S_{i,STC}$	kw/m^2	1
k	-	1.75
c	-	8.78
α	-	6.38
ω	-	3.43

Table 7. Results of economic dispatch using AR-ABC for the first case study.

Hour	WT	PV	FC	Utility	MT	Battery
1	0	0	30	30	6	-14
2	0	0	30	30	6	-16
3	0	0	30	30	6	-16
4	0	0	30	30	6	-15
5	0	0	30	30	6	-10
6	0	0	30	30	6	-3
7	0	0	30	30	6	4
8	0	0	30	30	6	9
9	1.7855	0	30	-15.7855	30	30
10	3.0900	7.5030	30	-21.5930	30	30
11	8.7750	9.2250	30	-30	30	30
12	10.413	3.5870	30	-30	30	30
13	3.9228	0	30	-21.9228	30	30
14	2.3766	9.6234	30	-30	30	30
15	1.7855	0	30	-14.7855	30	30
16	1.3050	0	30	-11.3050	30	30
17	0	0	30	-5	30	30
18	0	0	30	22	6	30
19	0	0	30	30	6	24
20	0	0	30	21	6	30
21	1.3017	0	30	-13.3017	30	30
22	0	0	30	-19	30	30
23	0	0	30	30	6	-1
24	0	0	30	30	6	-10

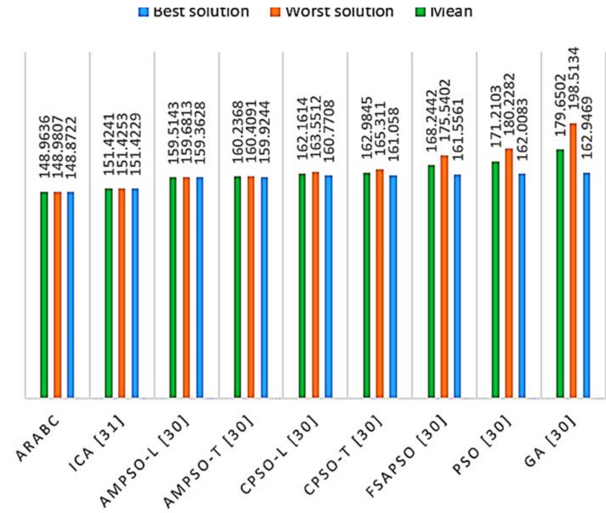

Fig. 8. Comparing the total cost for the first case study (€ct).

help to supply power. FC produces power at its maximum capacity because it is economical.

- At 8 am: It is the same as 7 am, with the difference that PV generation contributes to grid electricity generation.
- From 9 to 17: The price of electricity in the market is high, all the units produce electricity, so that they can sell electricity to the main grid and make a profit. The battery is discharging at full capacity to help provide power and profit. FC, MT, WT and PV are economical; so, they produce power at their maximum capacity. All the excess power of the micro-grid is injected into the main grid to be sold in the electricity market.
- At 17:00: The price of electricity is slightly cheap; so, electricity is bought from the grid. In order to prevent the complete discharge of the batteries, it is necessary to allocate the excess power production to the battery storage while meeting the load demand; so, MT and FC produce power at their maximum capacity.
- From 18:00 to 20:00: It is the same as 17:00, but at this hour, electricity is not produced by PV.
- From 21 to 22: It is the same as at 20, but at this time, electricity is not produced by PV and the need for electricity is higher.
- At 23: The maximum possible power is received from the grid, which makes MT, the costs of which are more than Utility to produce power with its minimum capacity. Because it is cost-effective, FC produces power at its maximum capacity. Excess production is used to store batteries.
- At 24: Due to the low price of electricity, the maximum possible power is purchased from the grid which causes the MT to turn OFF. FC is economical; so, it produces power at its maximum capacity. Excess production is used to store batteries. Figure 13 shows the graph of the total cost function related to the second case study.

5.3. Results of the Third Case Study

According to Figure 15, considering that buying and selling electricity from the grid are unlimited, the cost of VPP for the third case study is compared with the cost obtained by other algorithms. According to the obtained results, the AR-ABC algorithm imposes the lowest cost on the studied system. According to Figure 14 and Table 9, for the third case study, the results are as follows:

- From 1 to 7 am: PV does not produce electricity, the price of electricity is cheap in the market and electricity is completely purchased from the electricity market, which is very high

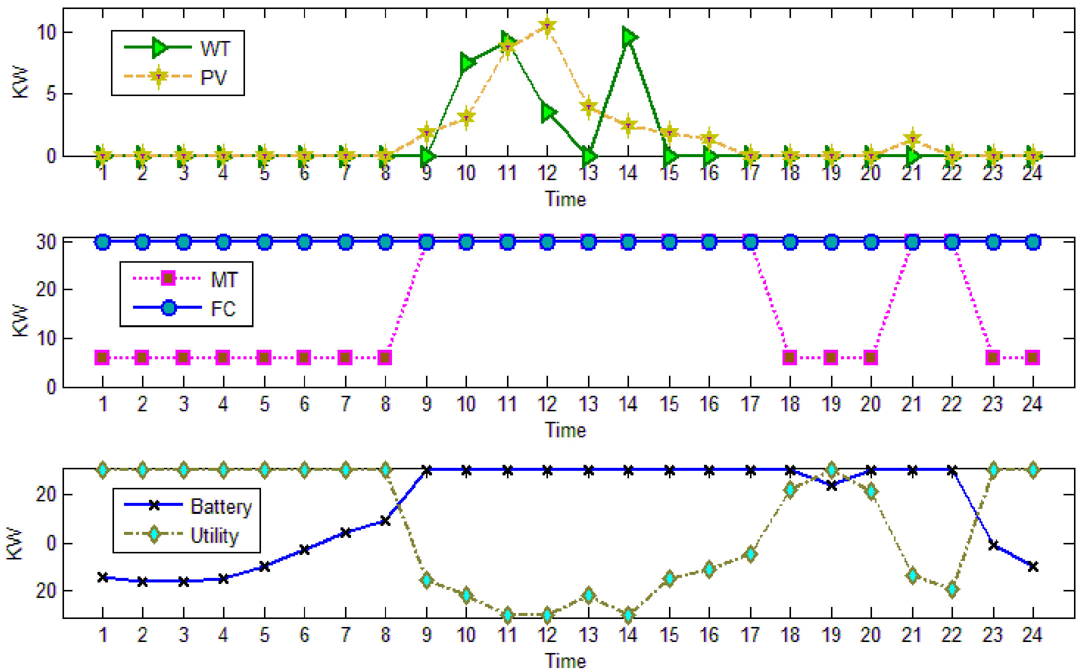

Fig. 9. Power generation diagram of the units in the first case study.

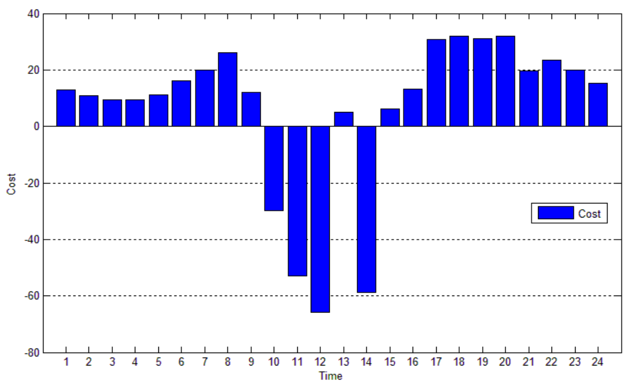

Fig. 10. The graph of the total cost function related to the first case study.

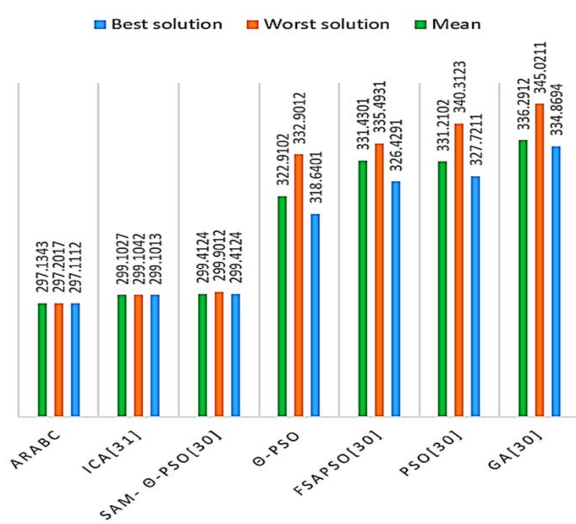

Fig. 11. Comparing the total cost for the second case study (€ct).

Table 8. Results of economic dispatch using AR-ABC for the second case study.

hour	WT	PV	FC	Utility	MT	Battery
1	1.785	0	30	30	20.215	-14
2	1.785	0	30	30	18.215	-16
3	1.785	0	30	30	18.215	-16
4	1.785	0	30	30	19.215	-30
5	1.785	0	30	30	24.215	-30
6	0.915	0	30	30	30	-27.915
7	1.785	0	30	30	30	-21.785
8	1.305	0.2	30	30	30	-16.505
9	1.7855	3.75	30	-19.5355	30	30
10	3.09	7.5279	30	-21.593	30	30
11	8.775	10.45	30	-30	30	28.775
12	10.413	11.964	30	-30	30	21.6230
13	3.9228	23.9	30	-30	30	14.1772
14	2.3766	21.05	30	-30	30	18.5734
15	1.7855	7.875	30	-23.6605	30	30
16	1.305	4.225	30	-11.305	30	30
17	1.785	0.55	30	30	30	-7.335
18	1.785	0	30	30	30	-3.785
19	1.302	0	30	30	30	-1.302
20	1.785	0	30	30	30	-4.785
21	1.3017	0	30	-13.3017	30	30
22	1.3005	0	30	-19	30	0.232
23	0.915	0	30	30	6	-1.915
24	0.615	0	30	30	0	-4.615

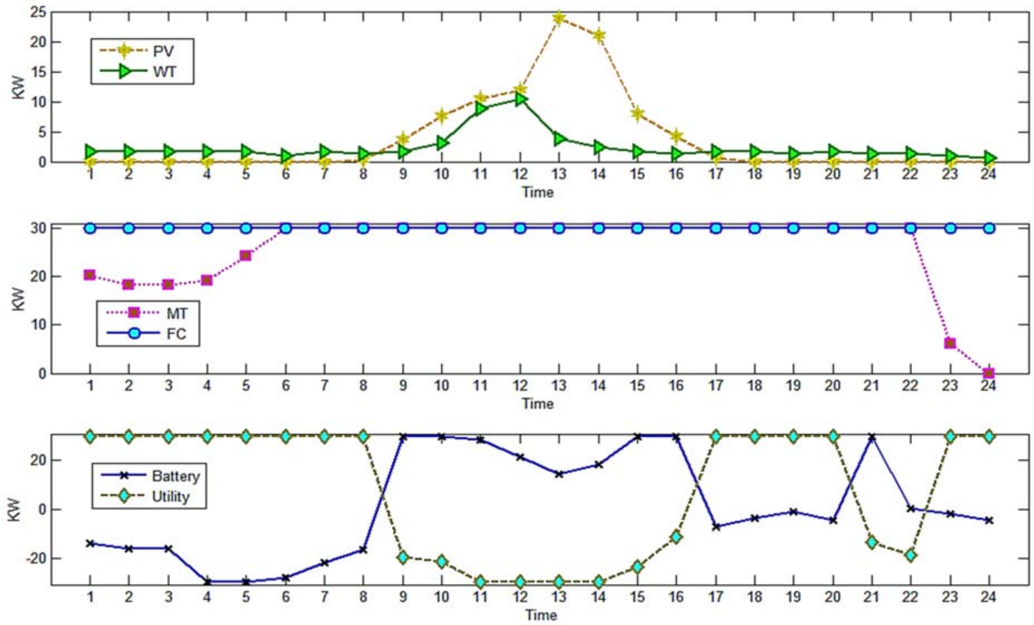

Fig. 12. Power generation diagram of the units in the second case study.

Table 9. Results of economic dispatch using AR-ABC for the third case study.

hour	WT	PV	FC	Utility	MT	Battery
1	0	0	3	73	6	-30
2	0	0	3	71	6	-30
3	0	0	3	71	6	-30
4	0	0	3	72	6	-30
5	0	0	3	77	6	-30
6	0	0	3	84	6	-30
7	0	0	3	91	6	-30
8	0	0	30	69	6	-30
9	1.7855	0	30	-15.7855	30	30
10	3.0900	7.5279	30	-21.6179	30	30
11	8.7750	10.4500	30	-31.2250	30	30
12	10.413	11.964	30	-38.3770	30	30
13	3.9228	0	30	-21.9228	30	30
14	2.3766	21.0500	30	-41.4266	30	30
15	1.7855	0	30	-14.7855	30	30
16	1.3050	0	30	-11.3050	30	30
17	0	0	30	-5	30	30
18	0	0	30	22	6	30
19	0	0	30	84	6	-30
20	0	0	30	21	6	30
21	1.3017	0	30	-13.3017	30	30
22	0	0	30	-19	30	30
23	0	0	30	59	6	-30
24	0	0	3	77	6	-30

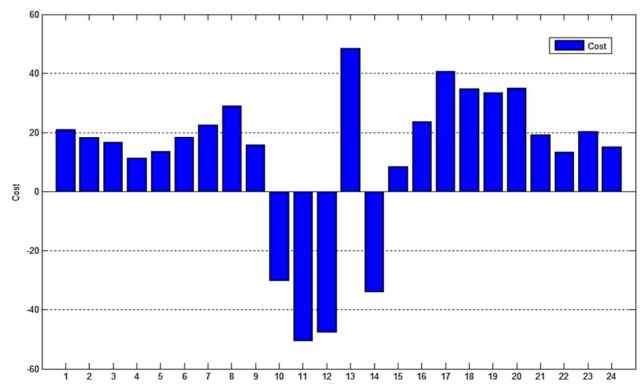

Fig. 13. The graph of the total cost function related to the second case study.

considering the unlimited power exchange with the electricity market. The battery is charged at maximum capacity. FC and MT are working at their minimum capacity. WT is not economical, so it is off.

- At 8 am: The battery is charged at maximum capacity and the MT works at its minimum capacity. FC works at maximum power and WT is turned off because it is not economical. PV produces electricity, but it is not economical, so it is off. All the surplus power produced by the units is sold in the electricity market.
- From 9 to 17: The price of electricity in the market is expensive; the battery injects power into the grid with its full capacity. WT is affordable, so it is ON. PV stays ON when the price of electricity is very expensive, but turns off when it is slightly expensive. FC and MT operate at their maximum capacity because they are economical.
- At 18: PV does not produce electricity, the price of electricity is cheap in the market and electricity is completely purchased from the electricity market. The battery is charged at maximum capacity. MT works at its minimum capacity. FC is working at its maximum capacity. WT is not economical,

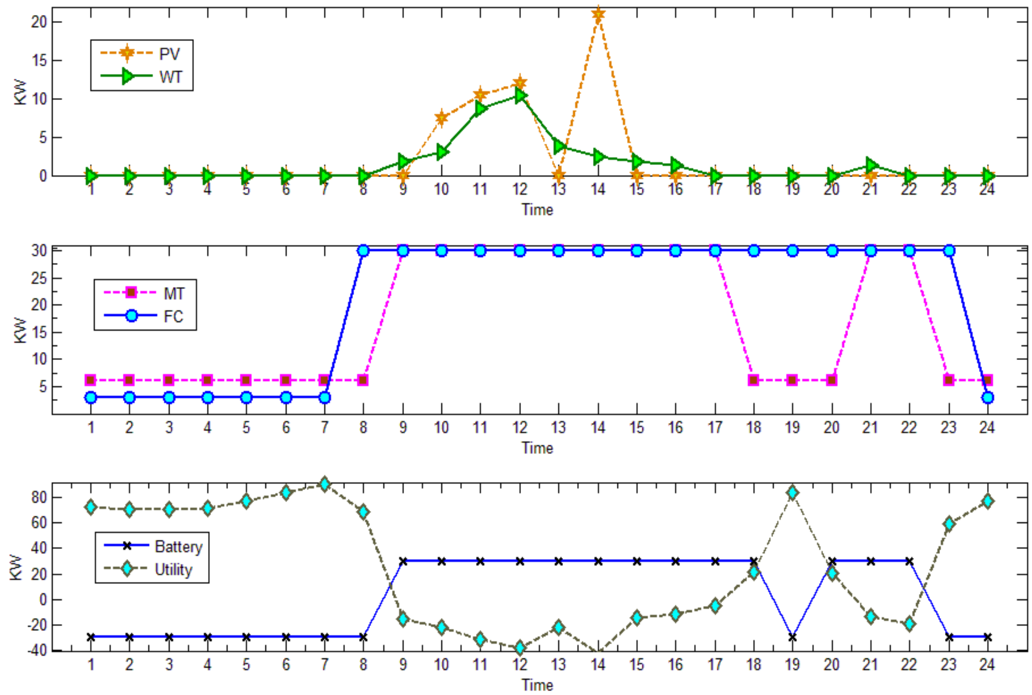

Fig. 14. Power generation diagram of the units in the third case study.

so it is off.

- At 19: The same as 20:00, but PV does not produce electricity.
- At 20:00: The price of electricity is cheap in the market and electricity is completely purchased from the electricity market. The battery is charged at maximum capacity. MT works at its minimum capacity. FC is working at its maximum capacity. WT is not economical, so it is off.
- At 21:00: The load demand increases slightly. Battery as well as FC and MT works at their maximum capacity because they are economical. WT is economical, so it is ON.
- At 22: There is a slight decrease in demand. Battery as well as FC and MT works at their maximum capacity because they are economical. WT is not economical, so it is off.
- At 23: The demand comes down again. FC works at its maximum capacity because it is economical. MT works at its minimum capacity because the load demand is low. WT is not economical, so it is off. The battery is fully charged.
- At 24: Load demand drops to such an extent that FC and MT work at their minimum capacity. WT is not economical, so it is off. The battery is fully charged. Figure 16 shows the graph of the total cost function related to the third case study.

6. CONCLUSION

In this research, to plan the VPP optimally and reduce generation and operation costs, a modified ABC was used. At the initialization stage of AR-ABC, the AR method was used to limit the search space for the problem solving process. When search space became limited and small, the points that were accepted had the highest probability of minimizing the objective function. To prevent employed bees from moving away from the initial optimal points, a movement step index was introduced. To avoid falling into the trap of local optimal points and to reach global optimal points, the movement phase index was very effective. In this paper, three case studies for VPP were analyzed and their results were compared with the results obtained from other algorithms, which showed the superior performance of the proposed algorithm. Also,

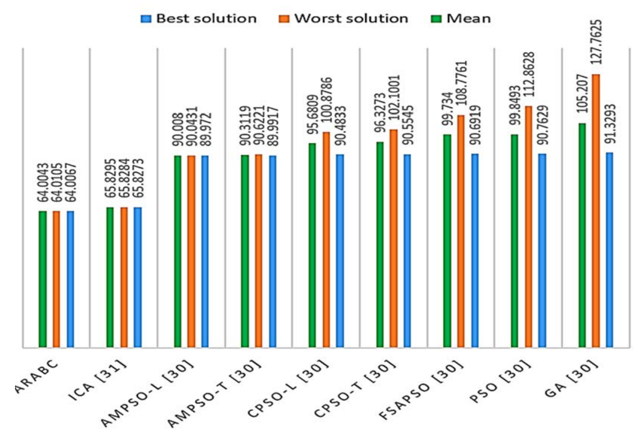

Fig. 15. Comparing the total cost for the third case study (€ct).

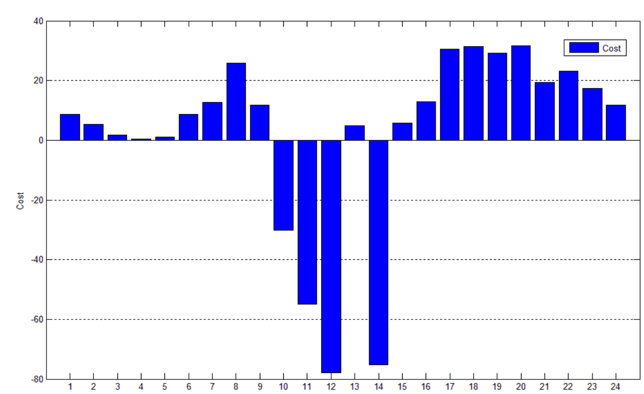

Fig. 16. The graph of the total cost function related to the third case study.

with the planning of the VPP and the exchange of electric power with the power market, it was found that the more the exchange of electric power with the power market (purchase and sale of power), the more profitable the network and the lower the costs of operation and power generation would be.

Suggestions for improvement and review of future works are presented as follows: 1) Investigating the effects of environmental issues in the studied network and the objective function; 2) Design, feasibility and planning of VPP in the presence of electric vehicles; 3) Using the capabilities of the AR method in other optimization problems; 4) Analyzing the AR method for solving probabilistic engineering problems; 5) The possibility of using the AR-ABC algorithm for combining with other algorithms and 6) Using the AR method for robust optimization algorithms.

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