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Conference Paper · November 2021

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PHASOR PARTICLE SWARM OPTIMIZATION FOR SOLVING PROBLEM OF PRICING IN ELECTRICITY MARKET

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Abstract

Minimization of fuel costs in thermal power plants by adjusting electric power outputs from generators represents important problem in power system operation and control. This problem affects also merit order and pricing in the electricity market. In this article, the Phasor Particle Swarm Optimization (PPSO), which represents a meta-heuristic self-adaptive and non-parametric algorithm, is proposed for solving the problems of generation cost minimization and pricing in the electricity market. Performance of PPSO for solving the cost minimization problem is evaluated using the standard IEEE 30-bus test system with 6 generating units. Based on the results obtained, the PPSO outperforms all other meta-heuristic algorithms that have been applied in published literature to solving this problem. In addition, the PPSO, cost minimization model and equilibrium supply chain model are used in the analysis of a case study based on a real electricity market, and in particular retail, spot and offer prices. Moreover, the results have shown that the proposed optimization approach can be used for merit order correction and for reducing electricity prices, increasing the amount of electricity sold (purchased), and improving the efficiency of a spot electricity market.

Keywords: electricity market, phasor particle swarm optimization (PPSO), pricing, supply chain management.

INTRODUCTION

This paper proposes the application of Phasor Particle Swarm Optimization (PPSO), one of the recently developed meta-heuristic algorithms [1], for solving the problem of fuel costs minimization in thermal power plants by adjusting electric power outputs from generators. The generation cost minimization model is then combined with the equilibrium supply chain (SC) model of the spot electricity market and prices are analyzed using the case study of a real market. The validation of the PPSO for generation cost minimization is carried out using the standard IEEE 30-bus test system with 6 generators and by comparing the obtained results with those corresponding to some other meta-heuristic algorithms. This paper analyzes how the optimized cost of generator group affects the pricing in a spot electricity market. In addition to this, the following is assumed: (i) The marginal generation cost of any generator represents its optimal offer price. (ii) Generators/producers and retailers participate in the spot market in which the electricity is trading at a common price, i.e. the spot price. (iii) The retailers sell the electricity purchased from generators to the consumers at a retail price. We determine the optimum retail price, which depends on the spot price and changes on an hourly basis. In order to obtain the optimal retail price, we use the supply chain (SC) model of the spot market and the Nash equilibrium, and determine the generalized demand function. In the context of a case study based on the Serbian electricity market, we derive the cost parameters from the offer curves relating to four producers that participate in the electricity market.

GENERATION COST MINIMIZATION

Usually, the fuel cost function of a generator is quadratic, i.e.

$$F_g\left(P_g\right) = a_g + b_g P_g + c_g P_g^2,\ g = 1, 2, ..., G \quad (1)$$

where F_g (\$/h) is the fuel cost of the g^{th} generator, P_g (MW) is the output power of the g^{th} generator, and a_g, b_g and c_g are the cost coefficients. The objective function in minimization is:

$$F=\sum_{g\in G}F_g\left(P_g\right) \tag{2}$$

Minimization is done with the specified limits on power of each generator, i.e.

$$P_g^{\min}\le P_g\le P_g^{\max} \tag{3}$$

where $P_g^{\min}$, $P_g^{\max}$ and P_g are the minimum, maximum and actual powers of the g^{th} generator, and with a given condition of balance between the generated power and the consumed power, i.e.

$$\sum_{g\in G}P_g-P_D=0, \tag{4}$$

where P_D is specified total power.

PSO AND PPSO

The PSO algorithm is inspired by swarm behavior in nature when searching for food [2]. Swarm units change their positions and velocities and gradually move towards the food source. In the PSO, each individual (particle, solution) in the swarm is represented by a position vector and a velocity vector, as follows:

$$X_i(t)=\left[x_i^1(t),\ldots,x_i^k(t),\ldots,x_i^n(t)\right] \tag{5}$$

$$V_i(t)=\left[v_i^1(t),\ldots,v_i^k(t),\ldots,v_i^n(t)\right] \tag{6}$$

where X_i *(t)* and V_i *(t)* are the position and velocity vectors of i^{th} particle in time (iteration) *t*, respectively; $x_i^k(t)$ and $v_i^k(t)$ are the position and the velocity of i^{th} particle, respectively, with respect to the k^{th} dimension.

The PPSO was proposed by authors of [1]. In the PPSO, the control parameters of the PSO are modeled with phase angle (θ), inspired from phasor theory. In such a manner, the PPSO becomes the self-adaptive algorithm. The velocity in each iteration is updated as follows:

$$V_i(t)=\left|\cos\theta_i(t)\right|^{2*\sin\theta_i(t)}\times\left(Pbest_i(t)-X_i(t)\right)+ \\ +\left|\sin\theta_i(t)\right|^{2*\cos\theta_i(t)}\times\left(Gbest(t)-X_i(t)\right) \tag{7}$$

where $Pbest_i(t)$ and $Gbest(t)$ are the personal and global best position vectors, respectively; X_i (*t*) is the current position vector for the i^{th} particle in t^{th} iteration; θ_i is the one-dimensional phase angle of the vector $\vec{X}_i\angle\theta_i$ for the i^{th} particle. For an initial population consisting of *N* particles (for *t* = 1), the vector $\vec{X}_i$ is: $\vec{X}_i=|X_i|\angle\theta_i$ (*i* = 1:*N*). Initially, *N* particles are randomly generated in the *n*-dimensional space of problem with a phase angle θ_i obtained from uniform distribution θ_i (5)
$= U$ (0, 2π), and with an initial velocity limit $V_{i,max}$. The lower and upper limits of V_i (*t*) are defined by the following interval [-$V_{i,max}$ (*t*), $V_{i,max}$ (*t*)].

The particle position is updated using the following equation:

$$\vec{X}_i(t+1)=\vec{X}_i(t)+\vec{V}_i(t) \tag{8}$$

(6)

After updating the particle velocity and position using the equations (7) and (8), respectively, the particle phase angle θ_i and the maximum velocity $V_{i,max}$ for the next iteration are calculated using the following equations:

$$\theta_i(t+1)=\theta_i(t)+\left|\cos\theta_i(t)+\sin\theta_i(t)\right|\times(2\pi) \tag{9}$$

$$V_{i,\max}(t+1)=\left|\cos\theta_i(t)\right|^2\times\left(X_{\max}-X_{\min}\right) \tag{10}$$

The flowchart of the PPSO is presented in Fig. 1.

SC MODEL

The SC model is similar to those in [3]. The model represents the equilibrium SC model of electricity market of spot structure (pool based). An equilibrium model is characterized by optimal conditions for any decision-maker in the SC, who competes with non-cooperative manner, following the concept of Nash [4]. The optimality conditions are expressed from the Nash equilibrium, which is derived for the SC. In an electricity market of spot structure, electricity is bought and sold on the spot market immediately (on the spot) at spot prices. The main functions of a pool are: determining the merit order, determining the prices for electricity traded, and ensuring sufficient capacity to maintain the system security.

The amount of electricity corresponding with the power $P_{s,g}$ is transacted between the generator *g* and the spot market. The retailer *r* buys the amount of electricity corresponding with the power P_r from the spot market at the common spot price *s* and sells it to the demand *D* at the retail price *d*. In that case, the equilibrium condition of the spot market is:

$$\sum_{g}^{G} P_{s,g} = \sum_{r}^{R} P_r \qquad (11)$$

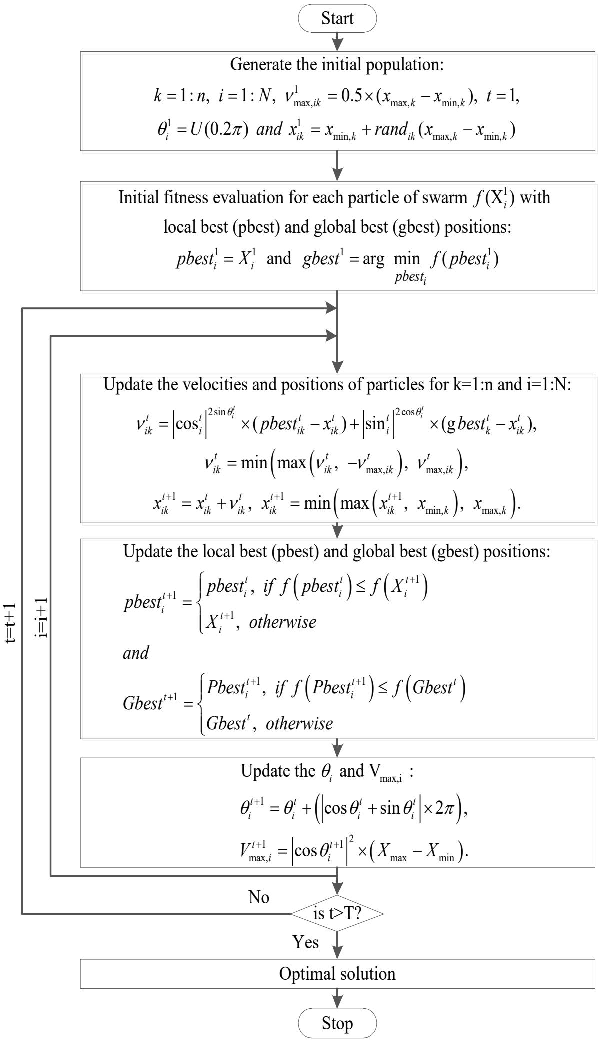

Fig. 1. *The flowchart of the PPSO.*

The power is expressed in MW, while the prices and profits are in \$/h. The power P_r of the retailer r is obtained by maximization of the retailer's profit. Retailer's profit Π_r can be expressed as:

$$\Pi_r = dP_r - sP_r = (d - s)P_r\,, \quad r = 1,...,R \qquad (12)$$

In this model, the retail price d is expressed as a generalized linear inverse function of powers P_r. This function represents the consumers' demand function (one demand function for all consumers) and has the shape such as the one defined in [3],

$$d = \kappa - \sum_{r}^{R} \varphi_r P_r\,, \quad \kappa \ge 0, \quad \varphi_r \ge 0, \quad r = 1,...,R \quad (13)$$

where φ_r represents the slope of the separate demand function (demand curve) of retailer r and differs for each retailer. The generalized function (13) would allow for differentiation between the retailers.

The spot price s is expressed from the first order derivative of the equation (12) equating it to zero (Nash equilibrium), i.e. from the condition under which each retailer maximizes its own profit:

$$\frac{\partial \Pi_r}{\partial P_r} = \frac{\partial d}{\partial P_r} P_r + d - s = 0\,, \quad r = 1,...,R \qquad (14)$$

From the equations (13) and (14) follows:

$$s = -\varphi_r P_r + \kappa - \sum_{r}^{R} \varphi_r P_r\,, \quad r = 1,...,R \qquad (15)$$

By summing all the R equations of the form (15) and by expressing s, it is obtained:

$$s = -\frac{R+1}{R} \sum_{r}^{R} \varphi_r P_r + \kappa\,, \quad r = 1,...,R \qquad (16)$$

Expressing the sum $\sum_{r}^{R} \varphi_r P_r$ from the equation (16) and substituting it in the equation (15), the value of power P_r of retailer r can be expressed as:

$$P_r = \frac{\kappa - s}{(R+1)\varphi_r} \qquad (17)$$

Summing the R equations of the form (17) and taking the equation (11) into account, the spot price s becomes:

$$s = \kappa - \frac{R+1}{\sum_{r}^{R} \frac{1}{\varphi_r}} \sum_{g}^{G} P_{s,g} \qquad (18)$$

Expression (18) represents the aggregated demand curve for the spot electricity market.

TESTING THE PPSO

The PPSO algorithm is tested on the standard IEEE 30-bus system with six generators and a total load demand of 283.4 MW. Cost coefficients are taken from [6] (Table 1). The PPSO algorithm is implemented on a platform of 1.6 GHz with 3 GB RAM running MATLAB R2017a. All the results showed herein are the best values obtained over 30 runs. The error tolerance value in the equation (9) is $\delta = 10^{-6}$ MW. The results obtained using the PPSO are compared with those obtained using the following three algorithms: (i) hybrid Particle Swarm

Optimization-Gravitational Search Algorithm (PSOGSA) [5], as the best solver for the generator cost minimization problems [6], [23]; (ii) Butterfly Optimization Algorithm (BOA) [7], as one of the newest meta-heuristic algorithms; and (iii) Firefly Algorithm (FA) [8], as one of the most widely used algorithms.

The minimum, maximum, and standard deviation (SD) values for application of tested algorithms are presented in Table 2. According to Table 2, the minimum value of fuel cost obtained using the PPSO is the lowest in comparison with the minimum values obtained using the other algorithms. Also, the standard deviations related to the results obtained using the PPSO are the lowest compared to the standard deviations of the results obtained using the PSOGSA, FA and BOA. Table 3 shows the best solutions for the power outputs and fuel cost, obtained using the PPSO.

Fig. 3 shows the convergence behaviors of the PPSO, PSOGSA, FA and BOA algorithms in the case of the fuel costs minimization. According to Fig. 3, the PPSO converges to the minimum value in a number of iterations which is identical to that of the PSOGSA. Compared to the FA, the PPSO converges in a lower number of iterations. The number of iterations of the BOA is the lowest compared to the other ones, but according to Table 2, the BOA gives the poor values for the minimal fuel cost, emission and standard deviations. As Fig. 3 shows, ascend speeds are high at the beginning for all the four algorithms.

CASE STUDY OF THE SPOT MARKET

This subsection presents the results of a case study on the part of the Serbian deregulated electricity market, which is organized by the SEEPEX. The greater part (about 90%) of the Serbian electricity market is regulated by the PE Electric Power Industry of Serbia (PE EPS). More than 90% of electricity generation capacities (70% of which are thermal power plants) in Serbia are owned by the PE EPS. However, in order to reconcile the imbalances between the production and the consumption, the PE EPS sells a part of the produced electricity in the deregulated SEEPEX market. The main features of the SEEPEX spot market are as follows.

Producers and retailers participate in a day-ahead market in which the market operator collects the selling offers and the purchase bids to determine the spot price and the generation (consumption) electricity amounts corresponding to each producer (retailer) for each hour in the schedule. The spot market data that correspond with 5:00-6:00 p.m. (one particular hour) on January 30, 2020 (one arbitrary day) are used in the analysis carried out. The data are available at the web homepage of SEEPEX [9].

Table 1. Fuel cost coefficients and generation limits for the test system [6]

Gene-rator	a_g	b_g	c_g	P_g^{min}	P_g^{max}
1	10	200	100	5	150
2	10	150	120	5	150
3	20	180	40	5	150
4	10	100	60	5	150
5	20	180	40	5	150
6	10	150	100	5	150

Table 2. Minimum, maximum and SD values obtained using the PPSO, PSOGSA, FA and BOA

Algorithm	PPSO	PSOGSA	FA	BOA
Min	635.82129	635.82284	635.83288	640.37240
Max	647.29186	698.99430	642.65875	663.92341
SD	2.376452	18.37740	2.904691	5.989508

Table 3. The best solutions for the power outputs and fuel cost obtained using the PPSO

Generation, MW	
$P_{s,1}$	5.00000
$P_{s,2}$	13.44427
$P_{s,3}$	83.53982
$P_{s,4}$	74.84721
$P_{s,5}$	79.79982
$P_{s,6}$	28.65457
P_{loss}	1.88568
Fuel cost ($/h)	635.82129

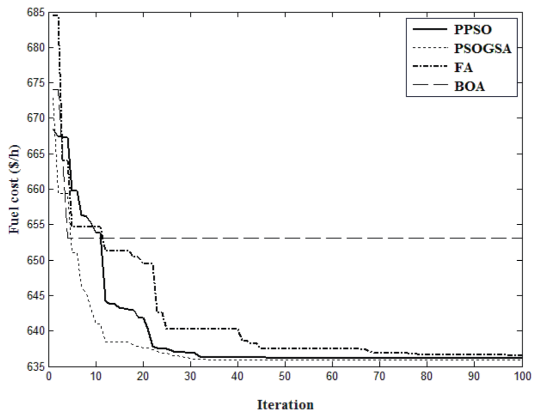

Fig. 3. *Convergences of PPSO, PSOGSA, FA and BOA.*

Fig. 4 shows the aggregated demand curve (curve 1) and merit order curve (curve 2), obtained for the resulting equilibrium spot price of 68.34 €/MWh and total generation (consumption) of 372.1 MWh. The previously mentioned data were reported by SEEPEX for the day and hour under consideration. As can be seen in Fig. 4 (curve 2), the six producers (p_1, p_2, p_3, p_4, p_5 and p_6) were accepted in the spot market for electricity delivery in the hour under consideration. In addition, Fig. 4 (curve 3) shows the optimized merit order curve that corresponds to the results listed in Table 4 and Table 5.

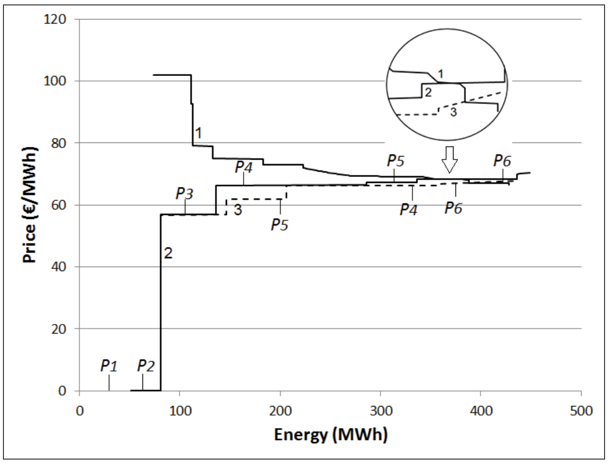

Fig. 4. *The stepwise aggregated demand curve for the hour under consideration (curve 1), the realized merit order curve for the hour under consideration (curve 2), and the optimized merit order curve (curve 3).*

The values for the parameters b_g and c_g of the generator (producer) cost function are obtained from the offer curve of each generator participating in the SEEPEX spot market for the hour under consideration (data available at [9]). The linear cost function represents the true marginal cost M_g of g^{th} generator, obtained as a derivative of the quadratic cost function F_g (P_g) (the equation (1)) with respect to P_g, that is, $M_g(P_g) = b_g + 2c_g P_g$. The intersection of this linear cost function and the y-axis correspond with the value of b_g, while its slope correspond with the value of c_g. The values for the parameters a_g of quadratic cost functions are not required because the minimization process, using the CEED model, generates the same values for output powers if $a_g = 0$.

Fig. 4 (curve 2) shows that the first two producers (p_1 and p_2) offered an unrealistically low price of electricity generated (0 €/MWh and 0.1 €/MWh). These are producers who cannot stop their production, since their offer prices are not based on the real costs. Table 4 outlines the values for the parameters b_g and c_g relating to producers. After linearization of the aggregated demand curve (5), it is found that the value of the parameter κ of 76.946 corresponds with the intersection of the linearized curve and the y-axis. The linearized aggregated demand curve is described by the following function: $s = -0.021 \cdot P + 76.946$.

Table 4 lists the best values of power P_g for each generator, obtained using the PPSO algorithm and CEED model, for the same total power of 355 MW offered by four generators that are accepted in the SEEPEX market for the hour under consideration. Based on Table 4, the optimal marginal costs, M_g for each of the four generators are calculated using the function $M_g(P_g) = b_g + 2c_g P_g$. The obtained results are listed in Table 5. Then, the value of optimized spot price is found at the intersection of the curve 3 and the curve 1 in Fig. 4, while the value of optimized retail price is obtained using the equations (16) and (20).

Table 4. The best solutions for the day under consideration, obtained using the PPSO

Producer	Generation, MW	Lower limit, MW	Upper limit, MW	b_g coefficient	c_g coefficient
p_3	64.99966	45	65	56.753	0.00090
p_4	150.16888	145	155	66.209	0.00035
p_5	59.87631	40	60	60.680	0.01000
p_6	79.95515	80	110	67.964	0.00050

Table 5. Realized and optimized prices for the day under consideration

	Marginal costs (offer prices) of producers, €/MWh				Spot price, €/MWh	Retail price, €/MWh
	p_3	p_4	p_5	p_6		
Realized prices	57.00	66.40	67.40	68.40	68.34	68.647
Optimized prices	56.870	66.314	61.877	67.972	67.79	68.085

Table 5 compares these optimized prices with the realized prices in the SEEPEX market. According to Table 5, the optimized spot and retail prices are lower than the realized ones. This means that the spot and retail prices are lower in the case of the generation costs minimization for the whole group of four generators than in the case when every single generator sets the price independently of the others. In addition to the lowered spot prices (67.79 €/MWh instead of 68.34 €/MWh) and retail prices (68.085 €/MWh instead of 68.647 €/MWh), according to Fig. 4, the application of the PPSO algorithm to optimize generation cost model would allow a greater amount of electricity to be sold in the spot market (387.8 MWh instead of 354.8 MWh). In this case, new (three) retailers are involved in the market, which were, according to the realized curve 2 in Fig. 4, disqualified in an auction (the total number of retailers increases from 27 to 30).

CONCLUSIONS

In this paper, the PPSO algorithm and generation cost model that was combined with the equilibrium SC model, were used for optimization of the offer prices, as well as for reduction of the spot and retail prices in the electricity spot market. The outputs of a group of generators from thermal power plants which are connected to the spot electricity market were adjusted so that their total production costs are minimal. The marginal costs of the generators were then determined as the offer prices in the spot electricity market. Also, the effects of the performed optimization on the merit order, spot price, retail price, total energy in the spot market, and number of retailers involved in the spot market were identified and adequately quantified.

In comparison with the real prices realized for the day and hour under consideration, the optimization framework applied to the case study of the Serbian electricity market gave a lower spot price, as well as a lower retail price. Moreover, it is shown that the proposed optimization approach would enable the spot market to transact a greater amount of electricity and to involve more retailers in the market, which would also lead to higher efficiency of the electricity market as a whole.

FUNDING

This work is funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

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