

Social welfare maximization based optimal energy and reactive power dispatch using ant lion optimization algorithm

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ABSTRACT

In this paper an optimal energy and reactive power dispatch problem is solved by using the ant lion optimization (ALO) algorithm by considering the total cost minimization and social welfare maximization (SWM) objectives. Two different market models are proposed in this work, i.e., conventional/sequential market clearing and the proposed/simultaneous market clearing. In each market model, two objectives, i.e., total cost minimization and SWM are considered. The conventional social welfare (SW) consists the benefit function of consumers and the cost function of active power generation. In this paper, the conventional SW is modified by including the reactive power cost function. The reactive power cost calculation is exactly same as that in the conventional practice. The most important difference is that instead of doing cost calculation in post-facto manner as in conventional practice, simultaneous approach is proposed in this work. The scientificity and suitability of the proposed simultaneous active and reactive power methodology has been examined on standard IEEE 30 bus test system.

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1. INTRODUCTION

The energy and reactive power dispatch are related to the optimal allocation of real power and reactive power generations, and it is used to optimize total generation cost from the conventional thermal generating units, maximize the social welfare, and minimize transmission losses and keeping all the voltages within the limits. With the introduction of restructuring of power industry, the power system operation has been changed significantly, and the important services of power system are unbundled into various markets like energy, reactive power, operating and spinning reserves (i.e., ancillary services) as well as the transmission markets. System operator (SO) is responsible for all these markets to maintain reliable and secure operation of the entire system [1]. In the restructured power systems, provision of reactive power support plays a vital role as an ancillary service, and it has significant impact on maintaining reliability and security of the power system. According to Federal Agency Regulatory Commission order 888 issued in April 1996, the reactive supply from generator is considered as an ancillary service [2].

The reactive power optimization problem in active distribution systems has been proposed in [3] by using the conic relaxation-based branch flow and it has been formulated as a mixed integer convex programming model. A robust chance constraint based reactive power dispatch model considering discrete reactive power compensators has been described in [4]. A new coordinated optimization approach for active

and reactive powers is formulated in [5] as a mixed integer 2nd order cone programming. Reference [6] proposes a new reactive power potential estimation approach based on two-stage optimization methodology by using the boundary bus voltage and uncertainty in distributed generators. An optimal reactive power scheduling problem by taking into account the small, medium and large-scale power systems by using the Chaotic bat algorithm is proposed in [7]. An optimal power scheduling approach for active and reactive power based economic model predictive controller is proposed in [8].

Recently most of the power system problems have been solved by using the evolutionary based algorithms. An enhanced firefly algorithm (EFA) for solving the optimal active and reactive power scheduling problem by accounting the uncertainties has been proposed in [9]. A cooperative dispatch methodology for optimal real and reactive power scheduling of wind energy generators to minimize the levelised production cost has been proposed in [10]. A data-driven local optimization of global objectives technique to control the reactive power dispatch from distributed energy sources is proposed in [11]. Reference [12] proposes a hierarchical distributed approach based on system of systems approach. The mathematical formulation and solution approach for the stochastic optimal reactive power scheduling by considering the wind, solar PV powers and load demand uncertainties has been proposed in [13].

The present paper proposes an approach to solve the complex issues associated with the restructured power system, i.e., solving energy and ancillary services markets simultaneously. The aim is to accommodate new-market related structure to the market clearing procedure. For simplicity, a sequential approach is used for every hour optimization, with generator ramp rate constraints. However, it can also be extended to full dynamic dispatch as well, if required depending on the market practice. In this work, the reactive power supplied by synchronous generators is considered as an ancillary service which should be compensated by the SO. Co-optimizing the provision of energy and reactive power gives the most economical dispatch of the two commodities from one source i.e., synchronous generator.

2. SEQUENTIAL AND SIMULTANEOUS MARKET CLEARING

Typically, the SO solves the market clearing problem by taking bids from generators and offers from load demands, and then finds the set of accepted bids and offers of generators and loads along with the market clearing price (MCP) [14]. Figure 1 depicts the conventional sequential and proposed simultaneous market clearing of active and reactive powers. Two different market models are presented in this paper, and they are presented as shown:

- **Market model 1:** Conventional/sequential market clearing.
- **Market model 2:** Proposed/simultaneous market clearing.

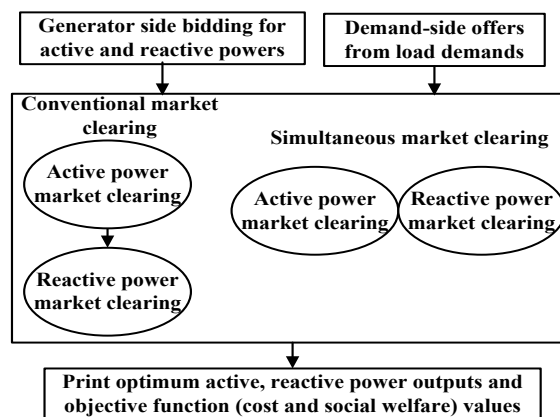


Figure 1. Conventional sequential and proposed simultaneous market clearing of active and reactive powers

2.1. Market model 1: conventional/sequential market clearing

In this market model, active power market is cleared first and then by using these results the reactive power market is cleared next. Generally, in any competitive electricity market, the problem of active power dispatch is formulated by using the cost minimization or social welfare maximization [15]. In this market model, two objective functions, i.e., fuel cost (FC) minimization and social welfare maximization (SWM) are considered.

2.1.1. Objective 1: fuel cost (FC) minimization

Here, the load demand is considered as inelastic to price. First, the active power dispatch problem is solved, after that reactive power dispatch problem is solved [16]. In this case, the objective is to minimize the total fuel cost of thermal generators, and it is formulated as,

$$FC = \sum_{i=1}^{N_G} C_{Gi}(P_{Gi}) = (a_{pi} + b_{pi}P_{Gi} + c_{pi}P_{Gi}^2) \quad (1)$$

N_G is number of generators, $C_{Gi}(P_{Gi})$ is the fuel cost function for active power generation (P_{Gi}). a_{pi} , b_{pi} and c_{pi} are generator energy cost coefficients for the i^{th} generating unit. In this conventional market clearing, after optimizing the real power cost minimization, reactive powers are known after actual implementation [17]. From the obtained reactive powers, reactive power cost is calculated using,

$$C_{Gi}(Q_{Gi}) = (a_{qi} + b_{qi}Q_{Gi} + c_{qi}Q_{Gi}^2) \quad (2)$$

where a_{qi} , b_{qi} and c_{qi} are the constants depending on power factor ($\cos \theta$), and they are determined by using [18],

$$a_{qi} = a_{pi} \quad (3)$$

$$b_{qi} = b_{pi} \sin \theta \quad (4)$$

$$c_{qi} = c_{pi} \sin^2(\theta) \quad (5)$$

Here, the total generation cost is the sum of the fuel cost (i.e., as shown in (1)) and the reactive power cost (i.e., as shown in (2)) [19].

2.1.2. Objective 2: social welfare maximization (SWM)

Generally, generator bids and load demand offers are considered for the market clearing process. When the demand-side bidding is introduced from the customers' side, then the fuel cost minimization objective changes to SWM objective. This social welfare (SW) concept is applied for the centralized market considering the demand elasticity [20]. SW represents the total surplus of customers and generators. This SWM objective can be expressed as,

$$SWM = maximize \left[\sum_{i=1}^{N_D} B_{Di}(P_{Di}) - \sum_{i=1}^{N_G} C_{Gi}(P_{Gi}) \right] \quad (6)$$

where,

$$B_{Di}(P_{Di}) = d_i - e_i P_{Di} - f_i P_{Di}^2 \quad (7)$$

N_D is the number of loads participating in the market clearing process, and $B_{Di}(P_{Di})$ is demand-side energy benefit function at bus i . d_i , e_i and f_i are demand-side bidding coefficients of i^{th} load/ demand.

2.2. Market model 2: proposed simultaneous market clearing

In this market structure, both the active and reactive power markets are cleared simultaneously. Here, the procurement of these services is obtained through the centralized dispatch, and it recognizes tradeoff between active and reactive powers. This market structure is considered as effective because the generator participates in both the markets simultaneously which allows it to use its inherent behaviour to get the maximum benefit.

2.2.1. Objective 1: total cost (TC) minimization

The traditional cost minimization objective consists only the active power cost of thermal generators. This traditional cost minimization objective is now modified to include the cost of reactive power in the objective function. This gives the most economical dispatch from a single source. Hence, the modified total cost minimization objective function is,

Minimize,

$$TC = \left(\sum_{i=1}^{N_G} C_{Gi}(P_{Gi}) + \sum_{i=1}^{N_G} C_{Gi}(Q_{Gi}) \right) \quad (8)$$

2.2.2. Objective 2: modified social welfare maximization (SWM)

The conventional SW function which consists of cost function of active power generation and benefit function of customers is now modified to include the cost function of reactive power generation. Hence, the modified SWM objective function is formulated as [21], maximize,

$$SWM = maximize \left[\sum_{i=1}^{N_D} B_{Di}(P_{Di}) - \left(\sum_{i=1}^{N_G} C_{Gi}(P_{Gi}) + \sum_{i=1}^{N_G} C_{Gi}(Q_{Gi}) \right) \right] \quad (9)$$

The above objective functions (i.e., as shown in (1), (2), (8) and (9)) are solved subjected to the following equality and inequality constraints.

2.3. Equality constraints

These constraints include the active and reactive power balance equations, and they are expressed as [22],

$$0 = P_{Gi} - P_{Di} - V_i \sum_{j=1}^n V_j |Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i), i \in (N_{PQ} + N_{PV}) \quad (10)$$

$$0 = Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^n V_j |Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i), i \in (N_{PV}) \quad (11)$$

Where $Y_{ij} = |Y_{ij}| \angle \theta_{ij}$, $v_i = V_i \angle \delta_i$ and $v_j = V_j \angle \delta_j$. N_{PV} and N_{PQ} are the number of generator and load buses, respectively. P_{Gi} and P_{Di} are active powers at generator and load buses. Q_{Gi} and Q_{Di} are reactive powers at generator and load buses.

2.4. Inequality constraints

2.4.1. Generator constraints

Generators active power (P_{Gi}), reactive power (Q_{Gi}) and voltage magnitudes (V_{Gi}) are limited by their minimum and maximum limits [23].

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, i = 1, 2, \dots, N_G \quad (12)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}, i = 1, 2, \dots, N_G \quad (13)$$

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max}, i = 1, 2, \dots, N_G \quad (14)$$

2.4.2. Demand limits

In elastic load demand, the limits on power demand can be expressed as,

$$P_{Di}^{min} \leq P_{Di} \leq P_{Di}^{max}, i = 1, 2, \dots, N_D \quad (15)$$

where P_{Di}^{min} and P_{Di}^{max} are minimum and maximum power demands at i^{th} bus. In an inelastic load demands, these two limits are equal, i.e., $P_{Di}^{min} = P_{Di} = P_{Di}^{max}$.

2.4.3. Constraints on transformer

These constraints are expressed as,

$$T_i^{min} \leq T_i \leq T_i^{max}, i = 1, 2, \dots, N_T \quad (16)$$

2.4.4. Reactive power capability constraints of synchronous generator

The active power output obtained from a synchronous generator is limited by the prime mover of the generator, whereas the capability of reactive power is limited by armature and field currents, and they are expressed by using as shown (17) and (18), respectively [24].

$$P^2 + Q^2 \leq V_t I_a \quad (17)$$

$$P^2 + \left(Q + \frac{V_f^2}{X_s} \right)^2 \leq \left(\frac{V_t E_{af}}{X_s} \right)^2 \quad (18)$$

2.4.5. Constraints on switchable VAR sources

These constraints are expressed as,

$$Q_{ci}^{min} \leq Q_{ci} \leq Q_{ci}^{max}, i = 1, 2, \dots, N_C \quad (19)$$

2.4.6. Security constraints

These include the load bus voltage magnitudes (V_{Di}) and line flow (S_{Li}) constraints, and they are expressed as,

$$V_{Di}^{min} \leq V_{Di} \leq V_{Di}^{max}, i = 1, 2, \dots, N_D \quad (20)$$

$$S_{Li} \leq S_{Li}^{max}, i = 1, 2, \dots, N_D \quad (21)$$

3. ANT LION OPTIMIZATION (ALO) ALGORITHM

ALO is an evolutionary based algorithm which models the interaction between the ants and ant lions in our nature. ALO mimics hunting behavior of ant lions. Two important stages involved in this algorithm are larvae stage (i.e., hunting prey) and adult stage (i.e., reproduction) [25], [26]. Various steps/operations involved in implementing this algorithm include random walk of ants, building of traps, and entrapment of the ants in ant lion pits, adaptive shrinking of traps, catching preys and rebuilding traps [27]. Figure 2 presents the flow chart of ALO technique for solving the proposed optimal energy and reactive power dispatch problem. For more details on ALO algorithm, the reader may refer references [28], [29].

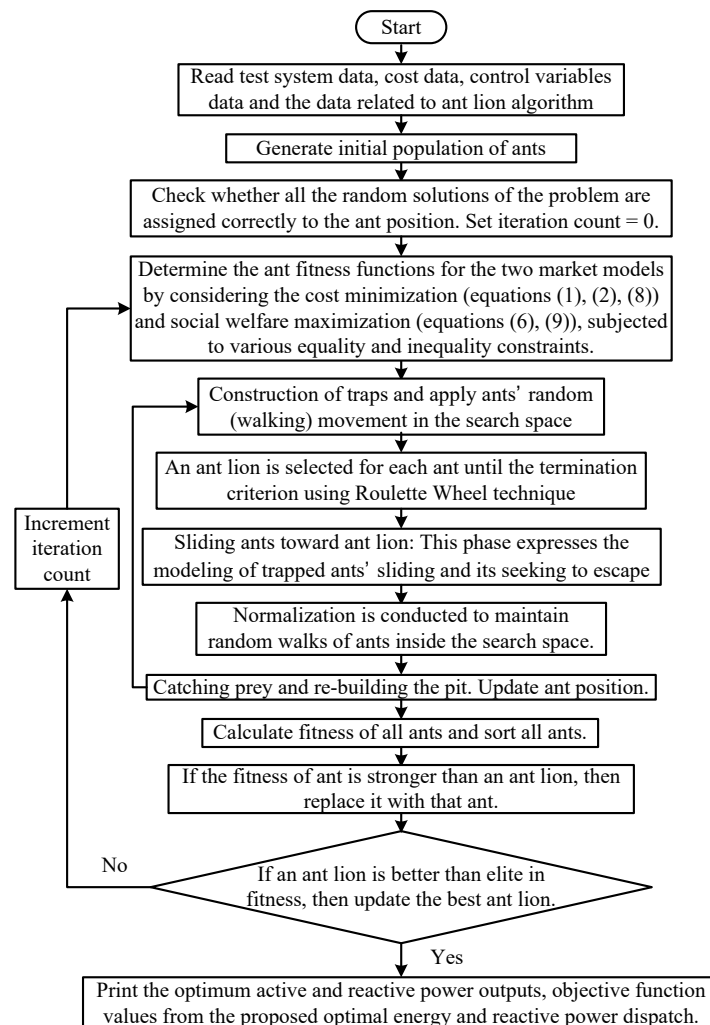


Figure 2. Flow chart of ALO algorithm for solving the proposed optimal energy and reactive power dispatch

4. RESULTS AND DISCUSSION

In this paper, standard IEEE 30 bus test system is selected to show the suitability of the proposed simultaneous energy and reactive power dispatch approach. This test system data including the generator data, bus data, line data, lower and upper limits of control variables considered in this work has been taken from reference [30]. The total load/demand is 283.4 MW. In this paper, population size/search agents and maximum number of iterations considered are 50 and 100, respectively. The experimental findings reported in this paper are the best results obtained over 30 runs for each case under study. Simulations are carried out on a MATLAB R2018a software in a personal computer-Intel Core i7, 3.6 GHz processor with the RAM of 8 GB. The fuel cost coefficients, lower and upper power limits of generators for IEEE 30 bus system are depicted in Table 1.

Table 1. Cost coefficients of synchronous generators.

Bus number	Generator number	a (\$/h)	b (\$/MWh)	c (\$/MW ² h)	P_{Gi}^{min} (MW)	P_{Gi}^{max} (MW)
1	1	0	2	0.00375	50	200
2	2	0	1.75	0.0175	20	80
5	3	0	1	0.0625	15	50
8	4	0	3.25	0.00834	10	35
11	5	0	3	0.0250	10	30
13	6	0	3	0.0250	12	40

4.1. Results for market model 1: conventional/sequential market clearing

In this market clearing model, the objective function does not include the cost of reactive power. The reactive power cost is calculated after optimizing the conventional objective function, i.e., the minimization of fuel cost minimization or the maximization of social welfare. In this market model 1, two case studies are simulated considering the minimization of fuel cost and maximization of social welfare as objective functions. These objectives are solved by using the ant lion optimization (ALO) algorithm.

4.1.1. Market model 1-case 1: fuel cost minimization

In this case, the fuel cost minimization (i.e., as shown in (1)) is optimized independently. Reactive power schedules and reactive power cost are calculated after the optimization. Table 2 presents the scheduled real and reactive powers for conventional market clearing with fuel cost minimization objective (market model 1-case 1). Here, the optimum fuel/real power generation cost obtained is 801.29 \$/h. The reactive power schedules are calculated after optimizing the fuel cost, and then the reactive power cost is calculated using the (2). The obtained reactive power cost is 433.06 \$/h. Hence, the total cost is 1234.35 \$/h, which is the sum of real power cost (801.29 \$/h), and reactive power cost (433.06 \$/h).

Table 2. Scheduled active and reactive powers and objective values for market model 1-case 1.

Generator number	Active power (in MW)	Reactive power (in MVAr)
1	174.27	93.27
2	47.58	4.21
5	23.92	-14.98
8	15.39	-35.78
11	15.69	61.29
13	15.12	22.31
Active power cost=801.29 \$/h		
Reactive power cost=433.06 \$/h		
Total cost=1234.35 \$/h		

4.1.2. Market model 1-case 2: social welfare maximization (SWM)

The objective considered in this case is the conventional SWM (i.e., as shown in (6)). Table 3 shows the scheduled real and reactive powers for conventional market clearing with SWM objective (market model 1-case 2). First, the conventional social welfare (SW) is optimized, and then the reactive power schedules are calculated after the optimization. The reactive power generation cost is calculated using as shown in (2). The modified SW is calculated after incorporating the reactive power cost from the original SW. Hence, the obtained SW is 262.94 \$/h, and amount of load served is 262.46 \$/h.

4.2. Results for market model 2: proposed simultaneous market clearing

4.2.1. Market model 2-case 1: total cost minimization

Here, the active and reactive power costs are optimized simultaneously (i.e., by using as shown in (8)), and the obtained scheduled powers and objection function values are shown in Table 4. The total generation cost obtained is 1129.83 \$/h, which includes real power cost of 820.67 \$/h and the reactive power generation cost of 309.1585 \$/h. This shows that, there is 8.47% saving in total cost, while optimizing both real and reactive power costs simultaneously as compared to conventional/sequential market clearing (market model 1-case 1).

Table 3. Scheduled real and reactive powers and objective values for market model 1-case 2.

Generator number	Active power (in MW)	Reactive power (in MVaR)
1	166.29	93.90
2	45.98	7.01
5	20.36	-3.84
8	15.11	-45.06
11	10.85	42.67
13	12.19	27.77
Active power cost=726.79 \$/h		
Reactive power cost=393.95 \$/h		
Total generation cost=1120.74 \$/h		
Total demand cost=1383.69 \$/h		
Modified social welfare=262.94 \$/h		
Amount of load served=262.46 MW		

Table 4. Scheduled active, reactive powers and objective values for market model 2-Case 1.

Generator number	Active power (in MW)	Reactive power (in MVaR)
1	190.55	-18.58
2	26.48	39.43
5	21.71	32.54
8	14.93	29.33
11	12.06	23.84
13	27.97	39.06
Active power cost=820.67 \$/h		
Reactive power cost=309.16 \$/h		
Total cost=1129.83 \$/h		

4.2.2. Market model 2-case 2: social welfare maximization (SWM)

In this case, the modified SW (i.e., as shown in (9)) is optimized, and the obtained scheduled real and reactive powers, and objective values are shown in Table 5. The optimum value of SW obtained is 324.92 \$/h, which is more than the SW obtained from market model 1-case 2 (i.e., 262.94 \$/h). The amount of load served in this case is 274.59 MW, which is higher compared to load served in market model 1-case 2 (i.e., 262.46 MW). This indicates that, there is 23.57% increase in SW, and 4.62% increase in amount of load served as compared to the corresponding values in market model 1-case 2. The investigations reveal the benefit of optimizing active and reactive power costs together. It is important to note that the reactive power cost calculation is consistent with the present market practice.

Table 5. Scheduled active, reactive powers and objective values for market model 2-case 2.

Generator number	Active power (in MW)	Reactive power (in MVaR)
1	187.03	-19.43
2	24.81	34.42
5	23.32	35.68
8	17.52	34.05
11	17.02	32.82
13	15.73	24.27
Active power generation cost=787.91 \$/h		
Reactive power generation cost=305.12 \$/h		
Total generation cost=1093.03 \$/h		
Total demand cost=1417.95 \$/h		
Social welfare (SW)=324.92 \$/h		
Amount of load served=274.59 MW		

5. CONCLUSIONS

In this paper, simultaneous/joint energy and reactive power market clearing is proposed based on the minimization of total generation cost or the maximization of social welfare. The conventional cost and social welfare objectives are modified to include the cost of reactive power. The most important difference is that instead of doing cost calculation in post-facto manner as in conventional practice, simultaneous approach is proposed in this work. The case studies on IEEE 30 bus system present the benefit of clearing the real and reactive power markets simultaneously over the conventional market clearing process. Simulation results shows considerable reduction in total cost, and an improved social welfare using proposed simultaneous approach.

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