Multi-Objective Unit Commitment With Renewable Energy Using GSA Algorithm

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Received: 29 April 2016 / Accepted: 6 May 2016 / Published online: 27 May 2016
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Abstract With increasing concerns of global warming and environmental change caused by the burning of fossil fuels, the operating paradigm of power system is shifting from minimum cost to minimum cost with minimum emission approach. Due to conflicting nature of economic and emission objectives, the generation scheduling becomes a multi-objective problem. In this paper, a multi-objective gravitational search algorithm (MOGSA) is used to provide Pareto optimal solutions which present the possible trade-off between the cost and emission objectives of unit commitment (UC) problem. The MOGSA technique is used for solving the environmental and economic dispatch problem considering hydro, pump storage plant, wind farm and solar farm, with and without ramp rates. The simulation results demonstrate the effectiveness of the proposed approach in solving multi-objective UC problem.

Keywords Unit-commitment · Renewable energy sources · Economic dispatch · Emission dispatch · Multiobjective gravitational search algorithm

List of symbols

a_i, b_i, c_i Cost coefficients of the i th generating unit
 $\alpha_i, \beta_i, \gamma_i$ Emission coefficients of the i th generating unit
 CC_i/H_i Cold/hot start cost of i th thermal unit
 $D_L(t)$ System load demand at hour t
 F_T/E_T Cost and emission over the scheduling horizon

G_t Forecast solar radiation at hour t
 G_{st} Solar radiation in the standard environment
 $I_i(t)$ Schedule state of i th thermal unit at hour t
 NT/NH Number of thermal/hydro units
 $Ph_k(t)$ Generation of k th hydro unit at hour t
 $P_i(t)$ Generation of i th thermal unit at hour t
 $P_{(max, min),i}$ Max and min output power of unit i
 $P_{(max, min),P,G}$ Max and min output power of PSP
 $P_i^{max}(t)$ Max generation of i th thermal unit at hour t
 $P_i^{min}(t)$ Min generation of i th thermal unit at hour t
 $P_{PG}(t)$ Pumping and generation of PSP unit at hour t
 $P_{Sn}(t)$ Rated power output of the PV generator
 $P_{WT}(t)$ Total actual wind generation at hour t
 P_{WN} Rated wind power output
 $TO_k(t)$ Turbine out flow for reservoir k during hour t
 $TO_{k(max/min)}$ Max/min turbine water out flow for reservoir k
 $SR(t)$ Spinning reserve at hour t
 RU_i/RD_i Ramp-up and down rate of unit i
 ST_i Startup cost of i th thermal unit
 $SO_k(t)$ Spilled outflow to the reservoir k during hour t
 $t_{OFFi}(t)/t_{ONi}(t)$ Time period that i th thermal unit has been continuously down/up till period t
 $T_{OFF/ON,i}$ Minimum down/up time of i th thermal unit
 $Vh_k(t)$ Volume of water for reservoir k during hour t
 $Vh_k^{max/min}$ Max/min volume of water for reservoir k
 $V_{psp}(t)$ Volume of reservoir in PSP during hour t
 $V_{psp}^{max/min}$ Max/min volume of reservoir in PSP
 $v_w(t)$ Wind speed at hour t
 v_1, v_2, v_3 Cut-in, rated and cut-out wind turbine speed
 $WI_k(t)$ Water inflow to the reservoir k during hour t
 ρ_k Input/output characteristics of k th hydro unit

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Introduction

The rise of environmental protection and the depletion of fossil energy sources have motivated to integrate the renewable energy sources into existing power system. This integration not only minimizes emissions (NO_x , CO_2 , SO_2 , small quantities of toxic metals, etc.) but also decreases total operating cost. Selecting the generating unit states to be ON and OFF during any interval of the day is known as a unit commitment (UC) problem (Wood and Wollenberg 1984), which is a complex non-linear mixed integer programming problem. It becomes more challenging in the presence of renewable energy sources and environmental constraints. Power generating units using fossil fuel emit harmful pollutants (CO_2 , SO_x , NO_x) into the atmosphere, which not only affects humans but entire living beings. Moreover, these pollutants may cause acid rain that is responsible for damaging forest and vegetation's as well as causing global warming. Seeing those concerns, US Clean Air Act Amendments in year 1990 forced utilities to reduce CO_2 , SO_x , and NO_x emissions from the thermal power plants. For that several strategies have been proposed (El-Keib et al. 1994; Helsin and Hobbs 1989) to reduce the atmospheric emissions. It was found that emission dispatching option in addition to the fuel cost objective is a better choice than other strategies which are highly expensive and may be termed as long-term options. Therefore objective of the optimization problem cannot be limited to only minimizing the fuel cost but also the gaseous emissions which is termed as environmental and economic dispatch problem (EED).

Research endeavors, therefore, have been focused on efficient, near-optimal UC algorithms which can be applied to large-scale power systems. Several methods have been proposed to solve the UC problem such as Lagrangian relaxation (LR) approach (Merlin and Sandrin 1983), genetic algorithm (GA) (Bakirtzis and Petridis 1996), evolutionary programming (EP) (Juste et al. 1999), simulated annealing (SA) (Mantawy et al. 1998), particle swarm optimization (PSO) (Shukla and Singh 2013) and gravitational search algorithm (GSA) (Roy 2013; Shukla and Singh 2014), etc.

Over the past few years, several researchers have proposed multi-objective evolutionary search strategies. Strength Pareto evolutionary algorithm (SPEA) (Abido 2003), multi-objective evolutionary algorithm (MOEA) (Abido 2006), multi-objective particle swarm optimization (MOPSO) (Wang and Singh 2008), multi-objective differential evolutionary (MODE) (Basu 2011) etc., constitute the pioneering multi-objective approaches that have been applied to solve the EED problem. Gravitational search algorithm (GSA) algorithm is a recent development which

is quite simple to implement to solve multi-objective optimal reactive power dispatch problem. GSA has less number of parameters and has good convergence characteristics. It is found that GSA is well suited to deal with non-smooth, non-continuous, non-differentiable and non-convex problems to provide better quality solutions with faster speed as compared to other methods discussed in literature (Bhattacharya and Roy 2012).

In this paper, a weighted sum method is used to convert a multi-objective optimization to a scalar optimization which assigns different weight to each objective function based on its importance. Multi-objective gravitational search algorithm (MOGSA) is combined with pseudo-code operators to create the new set of individuals from high potential individuals and further refines them to provide near optimal solution. A pseudo code based algorithm is suggested to deal with the equality constraints of the problem, other than penalty function method, for accelerating the optimization process. A fuzzy mechanism approach is used to achieve the best trade-off solution. The effectiveness of the proposed method is tested on a power system having ten thermal units, two hydro units (with one pumped storage unit), one equivalent wind power generation and one equivalent solar energy system.

Problem Formation

The problem formulation does not consider system configuration. The short-term unit commitment problem is formulated as follows:

$$\text{Minimize } F_T = \sum_{t=1}^T \sum_{i=1}^{NT} [I_i(t) \times F_i(P_i(t)) + I_i(t) \times (1 - I_i(t-1)) \times ST_i] \quad (1)$$

$$\text{Minimize } E_T = \sum_{t=1}^T \sum_{i=1}^{NT} [I_i(t) \times E_i(P_i(t))] \quad (2)$$

Economic Dispatch Problem (ED)

The total fuel cost in terms of real power output can be expressed as

$$F(P_i) = \sum_{i=1}^{NT} [a_i P_i^2 + b_i P_i + c_i] \quad (3)$$

Emission Dispatch Problem (EMD)

The emission function in terms of real power output can be expressed as

$$E(P_i) = \sum_{i=1}^{NT} [\alpha_i P_i^2 + \beta_i P_i + \gamma_i] \quad (4)$$

Power Balance Constraint

$$\sum_{i=1}^{NT} I_i(t) \times P_i(t) + P_{WT}(t) + \sum_{k=1}^{NH} Ph_k(t) + P_S(t) + P_G(t) = D_L(t) + P_L(t) + P_P(t) \quad (5)$$

assumption: power network losses $P_L(t) = 0$.

Thermal constraints

$$P_i^{\min}(t) \times I_i(t) \leq P_i(t) \leq P_i^{\max}(t) \times I_i(t) \quad (6)$$

$$P_i^{\max}(t) = \min\{P_{\max,i}, P_i(t-1) + \tau \times RU_i\} \quad (7)$$

$$P_i^{\min}(t) = \max\{P_{\min,i}, P_i(t-1) - \tau \times RD_i\} \quad (8)$$

$$T_{ON,i} \leq t_{ON,i}(t) \quad (9)$$

$$T_{OFF,i} \leq t_{OFF,i}(t) \quad (10)$$

$$ST_i = \begin{cases} HC_i & T_{down,i} \leq t_{off,i}(t) \leq T_{down,i} + CC_i \\ CC_i & t_{off,i}(t) > T_{down,i} + CC_i \end{cases} \quad (11)$$

where τ is equal to 60 min and it is UC time step.

Hydro constraints

$$Vh_k(t+1) = Vh_k(t) + WI_k(t) - TO_k(t) - SO_k(t) \quad (12)$$

$$Vh_k(1) = Vh_k^{begin} \quad (13)$$

$$Vh_k(T) = Vh_k^{end} \quad (14)$$

$$Ph_k(t) = \rho_k \times TO_k(t) \quad (15)$$

$$Vh_{k,\min} \leq Vh_k(t) \leq Vh_{k,\max} \quad (16)$$

$$TO_{k,\min} \leq TO_k(t) \leq TO_{k,\max} \quad (17)$$

Power output limits on wind energy system

The power output function with respect to the wind speed is given by

$$P_{WT}(t) = \begin{cases} 0 & : v_w(t) \leq v_1 \\ \psi(v_w(t)) & : v_1 \leq v_w(t) \leq v_2 \\ P_{WN} & : v_2 \leq v_w(t) \leq v_3 \end{cases} \quad \text{and } v_w(t) \geq v_3 \quad t = 1, 2, \dots, T \quad (18)$$

Power output limits on solar energy system

Power output from solar energy system is expressed as

$$P_{pv}(G_t) - P_b(t) - P_S(t) = 0 \quad t = 1, 2, \dots, T \quad (19)$$

$P_b(t) = 0$, because battery is not taken in consideration. R_c certain radiation point. Solar radiation-to-energy conversion functions of the PV generator is given by

$$P_{pv}(G_t) = \begin{cases} P_{sn} \frac{(G_t)^2}{G_{std} R_c} & 0 < G_t < R_c \\ P_{sn} \frac{G_t}{G_{std}} & G_t > R_c \end{cases} \quad t = 1, 2, 3, \dots, T \quad (20)$$

Pumped storage system

$$\text{Pumping : } P_{\min,P} \leq P_P(t) \leq P_{\max,P} \quad (21)$$

$$\text{Generation : } P_{\min,G} \leq P_G(t) \leq P_{\max,G} \quad (22)$$

$$V_{psp}^{begin} = V_{psp}^{end} \quad (23)$$

$$V_{psp}^{\min} \leq V_{psp}(t) \leq V_{psp}^{\max} \quad (24)$$

Generation Scheduling

Thermal unit scheduling with renewable energy sources is divided into T time interval (hours) so that the total fuel cost and total emission are minimized subject to the set of system and unit constraints. The system load demand, hydro unit data, wind speed and solar radiation must be known before the generation scheduling. The renewable-hydro-thermal coordination algorithm proposed, in this paper, is divided into different modules.

Multi-Objective Optimization and Pareto Optimality

Major real-world problems utilize the optimization of several objectives, which are often conflicting in nature. A general, multi-objective optimization problem with nm decision variable, mo objectives and several equality and inequality constraints can be formulated as follows

$$\text{Min}(y) = f(x) = (f_1(x), f_2(x), \dots, f_{mo}(x)) \quad (25)$$

$$\text{Subject to: } \begin{cases} g_j(x), & j = 1, 2, 3, \dots, K \\ h_k(x), & k = 1, 2, 3, \dots, L \end{cases} \quad (26)$$

where, K and L are number of equality and inequality constraints respectively. $x = (x_1, x_2, \dots, x_{nm}) \in X$ is the decision vector and X is the parameter space; $y = (y_1, y_2, \dots, y_{mo}) \in Y$ is the objective vector and Y is the objective space. The set of all Pareto-optimal solutions in the decision variable space is called as Pareto optimal set (Abido 2003, 2006). The corresponding set of objective vector is called as Pareto-optimal front or optimal trade-off solution as shown in Fig. 1.

Fig. 1 Pareto set and Pareto front

Gravitational Search Algorithm (GSA)

The GSA, a new optimization algorithm based on the law of gravity, was introduced by Rashedi et al. (Roy 2013) in (2009). In the proposed algorithm, agents are considered as objects and their performance is measured by their masses. Masses of the agents are directly proportional to their fitness function. During each iteration, masses attract each other due to gravitational force of attraction acting on them and these forces causes a global movement of all agents toward the agents with heavier masses.

A heavier mass means a more efficient agent.

Suppose the system with N agents, the position of i th agent is defined as:

$$Y_i = (y_i^1, y_i^2, \dots, y_i^k, \dots, y_i^\tau) \quad \forall i \in N \quad (27)$$

where, y_i^k is the position of i th agent in the k th dimension, τ is the dimension of search space. The gravitational force acting on i th agent due to j th agent at t th iteration is given as:

$$F_{ij}^k(t) = G(t) \times \left(\frac{M_j(t) \times M_i(t)}{ED_{ij}(t) + \varepsilon} \right) \times (y_j^k(t) - y_i^k(t)) \quad (28)$$

where, ε is a very small constant, $ED_{ij}(t)$ is the Euclidian distance between the i th agent and the j th agents which is defined as:

$$ED_{ij} = \|y_i(t), y_j(t)\|_2 \quad (29)$$

$G(t)$ is the gravitational constant at time t , which is initialized at the beginning and reduces with time to control the search accuracy and is given by:

$$G(t) = G_o \times e^{-\alpha t / Iter_{max}} \quad (30)$$

where, G_o is initial value of gravitational constant, α is constant term and $Iter_{max}$ ($= 100$) is the maximum number of iterations.

The total force acting on the i th agent is given by:

$$F_i^k(t) = \sum_{\substack{j=1 \\ j \neq i}}^{Kbest} rand_j \times F_{ij}^k(t) \quad (31)$$

where, $rand_j$ is random number in interval $[0,1]$, $Kbest$ is the set of l number of agents with heavier masses and best fitness value, and is evaluated in such a way that it decreases linearly with time and at last iteration, its value becomes 2 % of the initial number of agents.

According to Newton's law of motion, the acceleration of the i th agent at the t th iteration in k th direction is given as:

$$A_i^k(t) = \frac{F_i^k(t)}{M_i(t)} \quad (32)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad \text{and} \quad m_i(t) = \frac{fit_i(t) - worst(t)}{worst(t) - best(t)} \quad (33)$$

where, $fit_i(t)$ is the fitness value of i th agent at the t th iteration. The iterative best (t) and worst (t) values are given as:

$$best(t) = \min(fit_i(t)) \quad \text{and} \quad worst(t) = \max(fit_i(t)) \quad \forall i \in N \quad (34)$$

The updated velocity and position of each agent in the next iteration are calculated as

$$v_{ik}(t+1) = rand_i \times v_{ik}(t) + A_{ik}(t) \quad (35)$$

$$y_{ik}(t+1) = y_{ik}(t) + v_{ik}(t). \quad (36)$$

Multi-Objective GSA (MOGSA)

The single-objective GSA algorithm can be further extended to consider multi-objective by using weighted sum method. The bi-objective, combined economic emission dispatch (EED) problem is converted into single optimization problem by introducing the weighted sum method as follows: $0 \leq \lambda, \zeta \leq 1$ and $\lambda + \zeta = 1$

$$Min(F_T, E_T) = \sum_{t=1}^T \sum_{i=1}^{NT} \left[I_i(t) \times (\lambda F_i((P_i(t))) + \zeta E_i((P_i(t)))) \right. \\ \left. + I_i(t) \times (1 - I_i(t-1)) \times ST_i \right] \quad (37)$$

Table 1 Data for pumped storage plant

Plant	$P_{H\ i,k}(min)$	$P_{H\ i,k}(max)$	$V_{psp}(min)$	$V_{psp}(max)$	$V_{psp}(begin)$	$V_{psp}(end)$	ρ
PSP	25	300	250	1500	1000	1000	2/3

The multi-objective optimization techniques finally provide a set of Pareto-optimal solutions to the decision maker while optimizing a set of conflicting objectives. In this work, a pseudo code based algorithm (Shukla and Singh 2013) is developed to deal with equality constraints of the problem, other than penalty function. The main disadvantage of penalty function method is reduction of the search space and when the problem is highly constrained, the algorithm may spend a lot of time to find the feasible solutions.

Best Trade-off Solution

Once, a set of Pareto optimal solutions is obtained through MOGSA, power system operator needs to select one optimum solution, which will satisfy both the goals (minimum cost and minimum emission) to some extent. For this problem, the fuzzy membership function (Sakawa 1993), which represents the goals of each objective function, is used. Mathematical expression for membership function is as follows

$$\mu_i = \begin{cases} 1 & ; F_i \leq F_i^{\min} \\ \frac{F_i^{\max} - F_i}{F_i^{\max} - F_i^{\min}} & ; F_i^{\min} \leq F_i \leq F_i^{\max} \\ 0 & ; F_i \geq F_i^{\max} \end{cases} \quad i = 1, 2 \quad (38)$$

where, $F_i^{\max}$ and $F_i^{\min}$ are the maximum and minimum values from nondominated solutions of each of the objective functions, respectively. For each non-dominated solution, the normalized membership function μ^k is calculated as

$$\mu^k = \frac{\sum_{i=1}^{m_0} \mu_i^k}{\sum_{k=1}^{\mathfrak{R}} \sum_{i=1}^{m_0} \mu_i^k} \quad m_0 = 1, 2 \quad (39)$$

where, $\mathfrak{R}$ is the number of non-dominated solutions. The best compromise solution is the one having the maximum of μ^k .

$$Max = [\mu^k : k = 1, 2, \dots, \mathfrak{R}] \quad (40)$$

Test Results

The study system comprises of ten thermal units, two hydro units (with one PSP), one equivalent wind power generation and one solar system. The spinning reserve is assumed

Table 2 Cost and emission comparison

Cases	With out ramp rate		With ramp rate	
	Cost (\$)	Emission (ton)	Cost (\$)	Emission (ton)
CPSO for test 1				
ED	418,714.7	20,792.3	421,533.9	21,027.7
EED	422,737.4	17,669.2	426,022.9	17,684.9
EMD	429,682.5	15,286.7	432,582.1	15,535.2
CPSO for test 2				
ED	416,785.7	21,902.5	418,417.7	22,000.4
EED	418,736.1	20,266.4	421,332.8	19,804.1
EMD	422,647.0	18,567.1	424,968.4	18,352.8
GSA for test 1				
ED	417,747.5	20,939.9	419,894.2	20,920.7
EED	420,775.4	18,281.4	423,342.3	18,007.1
EMD	426,749.6	16,176.2	428,958.0	16,043.1
GSA for test 2				
ED	416,208.7	21,186.9	417,506.9	21,420.1
EED	418,499.7	19,084.7	420,589.1	19,052.7
EMD	421,948.2	17,696.7	424,703.1	17,495.2

to be 10 % of the load demand. The generator ramp rate constraints are set at 60 % of its rated capacity. The data of a ten units system and load is taken from (Shukla and Singh 2013). The hydro units' details, forecast solar radiation and wind velocity data are taken from (Shukla and Singh 2013). The intermittency of solar and wind power generations is not considered in this paper. Pumped storage data is given in Table 1. The selected tuned parameters for GSA are set as gravitational constant = 100, $\alpha = 10$. To test the effectiveness of the proposed method, two different tests are conducted with and without ramp.

Test 1: Thermal units with hydro, wind and solar.

Test 2: Same units mentioned in Test 1 and PSP.

Unit scheduling obtained from the proposed approach is same for different values of weights (economical scheduling where, $\lambda = 1$ and $\zeta = 0$). Cost and emission comparison of proposed approach with crazy particle swarm optimization (CPSO) is shown in Table 2. Simulation results confirms the superiority of the proposed approach. Figure 2 shows the power output from the renewable energy sources and pumped storage plant. Membership function for non-dominated solution with its maximum value and the distribution of non-dominated solutions obtained from the proposed approach with best trade-off solution for test 1 and test 2 are shown in Fig. 3a,

Fig. 2 Power output from different sources

Fig. 3 Best trade-off solution, a test 1, b test 2

b. It can be observed from Fig. 3 that the cost and emission both are increased due to the incorporation of unit ramp-rate characteristic and no objective (i.e., cost or emission) can be further improved without degrading the other.

Conclusion

In this paper, multi-objective gravitational search algorithm (MOGSA) is used to provide Pareto optimal solutions. The Pareto-optimal solutions present the possible trade-off between the cost and emission. To solve the problem, weighted sum method is applied to convert multi-objective optimization to scalar optimization. The proposed MOGSA is combined with pseudo-code operators to create new set of individuals from higher potential individuals and further refines them to provide near optimal solution. A fuzzy mechanism approach is used to achieve

the best trade-off solution. The feasibility and performance of the proposed approach is demonstrated on a test system. The results obtained using the proposed approach are encouraging and it is found that by efficiently utilizing the renewable energy sources, the total operating cost and emission of the system can be reduced significantly. The intermittency of solar and wind power generations is not considered in this paper, however, this can be considered as different of wind and solar power generations scenarios.

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