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Combined Economic Dispatch and Reliability in Power System by Using PSO-SIF Algorithm

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ABSTRACT
Reliability investigation has always been one of the most important issues in power systems planning. The outages rate in power system reflects the fact that more attentions should be paid on reliability indices to supply consumers with uninterrupted power. Using reliability indices in economic dispatch problem may lead to the system load demand with high reliability and low probability of power's outage rate. In this paper, the Economic Dispatch (ED) problem is optimized using the reliability indices. That is, ED problem and system reliability are proposed as Combined Economic Dispatch and Reliability (CEDR) problem. In CEDR problem, it is tried to utilize generating units in a way that we have high reliability in supplying the system load demand as well as the minimum fuel costs. Due to multi-objective and non-convex characteristics of this problem, Particle Swarm Optimization with Smart Inertia Factor (PSO-SIF) is used to solve the problem. In this research, the ED of power plants is successfully implemented in two systems with 6 and 26 generating units considering emission and system reliability.

KEYWORDS: Economic dispatch, Reliability, Particle swarm optimization, Smart inertia, Non-convex.

1. INTRODUCTION

Power supplying with high quality and uninterrupted to consumers is one of the main tasks of the power networks. The rate of supplying consumers' power demand with minimum outage is measured by reliability concept. Reliability is always one of the major aims in power systems [1] and is one of the most important factors in power systems planning, design, maintenance, and operation [2]. The reliability of a system is generally represented by its indices. Recent outages in power systems depict that the reliability indices should be more under attention in supplying consumers with uninterrupted power. The reliability indices play an important role in power system planning. In [3-5], the reliability parameters such as Loss of Load Probability (LOLP), Expected Energy Not Supplied (EENS) and Forced Outage Rate (FOR) are defined and explained. The concept of reliability can be investigated in three generation, transmission and distribution sections. In this paper, the reliability parameters are evaluated in the power generation section considering the Economic Dispatch (ED) problem.

The ED aims in thermal plants to minimize the plants fuel costs. This is accomplished in a system by determining the output power of the plants in a way that the total network power is supplied with the minimum cost amount and constraints satisfaction. For simplicity, the cost function of each power plant is specified by a quadratic function [6]. The mathematical approaches require some information about the derivation of the cost function. Unfortunately, the input-output characteristics of generation units are non-convex due to the prohibited operating zones, valve-point loadings and etc. The practical ED problem, considering constraints should optimize the non-convex problem which cannot be directly solved by the mathematical methods [7]. Hence, some advanced techniques such as Particle

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Swarm Optimization (PSO) and its improvement versions have been developed to optimize the economic dispatch problem.

In [8], a new hybrid particle swarm optimization algorithm was proposed and applied successfully to solve the dynamic economic dispatch problem with valve-point effects. The obtained results revealed the ability of this new version of PSO in solving ED problem. In [9], a hybrid Bacterial Foreign Algorithm and PSO (BFA-PSO) algorithm was reported for solving the economic load dispatch problem with valve-point loading effects. This method combines the advantages of both the bacterial foraging algorithm and PSO by incorporating the best bacterium in velocity in order to reduce the randomness and increase the swarming effect. In [10], the $\theta-PSO$ algorithm is proposed to solve non-convex ED problem considering practical constraints. The results show the ability of this improved version of PSO for solving ED problem with high constraints.

Particle swarm optimization with time varying acceleration coefficients is another improved version of PSO which proposed to solve multi-objective heat and power economic dispatch problem [11]. The obtain-ed results of this paper demonstrate the its superiority in solving non-convex and constrained combined heat and power economic dispatch problem.

PSO with Smart Inertia Factor (PSO-SIF) is another new and robust version of PSO implemented successfully in ED problems [12]. The obtained results of this paper prove the robustness and effectiveness of this method and show that it could be used as a reliable tool for solving optimization problems.

In order to optimize the multi-object function of this paper which aims to decrease the fuel cost of power plants along and greenhouse gases (GHGs) emission costs with system reliability enhancement, the PSO-SIF algorithm is applied.

PSO is a population-based search algorithm and searches in parallel using a group of particles. Kennedy and Oberhart presented the PSO algorithm based on the analysis of the behavior of birds and fishes [13]. In PSO, each particle tries to decide considering its previous experiences and that of its neighbors. The simple concept, easy implementtation, relative robustness to control parameters and computational efficiency are some of the advantages of the PSO algorithm [14-15].

In PSO, once the iteration increases, inertia weight and consequently the velocity of the particles will reduce. The concept of inertia weight was introduced in order to balance the local and global search. A high inertia weight during initial part of search ensures global exploration, while a low value leads to the end facilitated global convergence. Thus, if the algorithm is not able to find the optimum points in the initial iterations and with high inertia weight, it will not discover global points near the optimal point [12]. To overcome the problem of search area of PSO algorithm with increasing the iteration number, the present article puts forward a new method in which the value of inertia coefficient, unlike classic PSO, is smart and is not same for all the population.

The objective function of the proposed problem consists of plants fuel cost, emission costs and EENS. In order to investigate the functionality of the proposed method, the economic dispatching of the plants is accomplished on two systems with 6 and 26 units, aiming to decrease the system fuel cost, emission cost, and increase the system reliability.

2. FORMULATION OF THE PROBLEM

2.1. Objective function in proposed problem

In solving the Economic Emission Dispatch (EED) problem with reliability, it is aimed to decrease the plants fuel and emission cost, and at the same time increase the system reliability by applying it in solution process. Thus, the objective function of the problem is consists of three independent functions. The variables of the problem are the generated powers of plants defined as follows:

$[P_G]=[P_1,P_2,...P_n]^T$

minimizing: $F=[F_{FC},F_{GHG},EENS]$ (1)

Subjected to: $h(P_i)=0 \quad and \quad g(P_i)\le 0$

where n is the number of the last generator and P_i is the real power generated by the i^{th} generator. The parameter $h(P_i)$ is the equality constraint and $g(P_i)$ is the problem's inequality constraint. F is the multivariable objective function that should be minimized. The parameter F_{FC} is the fuel cost of the units and F_{GHG} shows the greenhouse gases emission costs. In the next, these functions are separately investigated before combining them in the objective function.

2.2. Economic dispatch formulation

Aim of ED problem is minimizing the cost function of the system considering the system constraints. The more details have been presented in [12, 16]. Generally, the simplified fuel cost function of each generation unit is as follows:

$$F_{FC} = \sum_{i=1}^{n} F_i(P_i) \tag{2}$$

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 \tag{3}$$

where, F_{FC} is the total generation cost, F_i is the cost function of the i^{th} generator, a_i , b_i and c_i are the cost coefficients of the i^{th} generator, P_i is the output power of the i^{th} generator and n is the last generator number.

In order to balance the power, an equality constraint should be satisfied. The total generated power should be the same as the total load demand (P_{Load}) as follows:

$$\sum_{i=1}^{n} P_i = P_{load} \tag{4}$$

The output power of each generator should correspond to the following inequality constraint:

$$P_{i,\min} \le P_i \le P_{i,\max} \tag{5}$$

where $P_{i,min}$ and $P_{i,max}$ are the minimum and maximum power amounts of i^{th} plant, respectively.

The generating units with multi-steam valve create more variations in plant cost function. Since the existence of steam valves leads to ripple in plants characteristics, the cost function would have a more nonlinear formula. Therefore, the cost function (3) should be replaced by the following cost function:

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 + |e_i \times \sin(f_i \times (P_{i,\min} - P_i))| \tag{6}$$

where e_i and f_i are the coefficients of generator i reflecting valve-point loading [12].

2.3. Emission formulation

It is aimed to decrease the released emission of fossil fuel of power plants. The emission from each unit depends on the power generated by that unit and can be modelled as the sum of a quadratic function [17], which is given by Eq. (7):

$$F_{GHG} = \sum_{i=1}^{n} h.EM_i(p_i) \tag{7}$$

$$EM_i(p_i) = ef_i(f_i + g_i p_i + h_i p_i^2) \tag{8}$$

Where $EM_i(p_i)$ is the GHGs emissions of thermal generator i; ef the fuel emission factor of GHGs for thermal generator; f_i,g_i, and h_i the fuel consumption coefficients of thermal unit; h is the given GHGs emission price which is determined by regulations and markets. The GHGs is CO_2 emission in this paper.

2.4. Reliability formulation

The target in the proposed problem is choosing the optimal generator power in such a way that the fuel cost and EENS of system reduce. The probability of any generation unit to be downed is equal to its *FOR* value.

In solving the CEDR problem, there are some generation units with different FOR value which each of the generation units produce a part of the power that is required by system. In calculating the amount of systems EENS our aim is creating a relationship between each unit's *FOR* value and amount of the production power of that unit. In a way that the units which has lower FOR value and consequently has more reliable quality participate more in producing the power required by system. In this way, we can compute the EENS of each unit that depends on the value of FOR and production power of each unit by using the following equations [4]:

$$EENS_i = FOR_i \times T \times P_i \quad (MWh) \tag{9}$$

$$EENS = \sum_{i=1}^{n} EENS_i \quad (MWh) \tag{10}$$

where n is the number of the last unit, T is the evaluation time interval in terms of hour and P_i is the i^{th} unit's power generation capacity in terms of MW. As it is shown in Eq. (9) in a constant value of EENS, more power will be produced by unit which has lower FOR. Eqs .(9) and (10) have been used to compute EENS in power market and deregulated systems [18].

2.5. Combination of ED, emission and reliability in objective function

The objective function of the proposed problem consists of three independent functions. Since the ED and emission cost, and EENS are in terms of ($/h) and MWh, respectively, and because the optimum values of functions are numbers with different range of values and the algorithm would not be able to similarly optimize all functions in the objective function, it is necessary to express each function in per unit form to enable the objective function to search optimum powers of plants in per unit. Another advantage of per unit form falls in the fact that it would be easy to indicate what percentage of each function is applied by the problem optimization. The objective function of the evaluated problem is as follows:

$$\begin{aligned} \min imize(F = \gamma \times F_{FC,pu} + \eta \times F_{GHG,pu} \\ + \mu \times EENC_{pu}) \quad (pu) \end{aligned} \tag{11}$$

where, $F_{FC,pu}$ is the fuel cost of the units in per unit based on its maximum value and is:

$$F_{FC,pu} = \frac{F_{FC}}{F_{FC,\max}} \quad (pu) \tag{12}$$

where the followings are valid:

$$F_{FC,\max} = \sum_{i=1}^{n} (a_i + b_i P_{i,\max} + C_i P_{i,\max}^2) \quad (\$/h) \tag{13}$$

$F_{GHG,pu}$ is the emission cost of the units in per-unit based on its maximum value and equals:

$$F_{GHG,pu} = \frac{F_{GHG}}{F_{GHG,\max}} \quad (pu) \tag{14}$$

$$F_{GHG,\max} = \sum_{i=1}^{n} h \times ef_i (f_i + g_i p_{i,\max} + h_i p_{i,\max}^2) \tag{15}$$

In Eq. (11), $EENS_{pu}$ is the per unit form of EENS based on its maximum value and equals to the following:

$$EENS_{pu} = \frac{EENS}{EENS_{\max}} \quad (pu) \tag{16}$$

where, the followings are valid:

$$EENS_{\max} = \sum_{i=1}^{n} FOR_i \times T \times P_{i,\max} \quad (MWh) \tag{17}$$

The parameters γ, η and μ are constants related to the influence percentage of each economic dispatch, emission and system reliability on objective function and it is necessary to be initialized in a way that the sum of these parameters be equal to one.

3. PARTICLE SWARM OPTIMIZATION

3.1. A review on PSO algorithm

Kennedy and Oberhart suggested the PSO algorithm based on individuals (particles or ingredients) behavior in a population. Its base refers to the Zoology and models of subjects' manner within a group. It seems that the group members share information between each other, which leads to group efficiency increasing. In this algorithm, each particle represents a solution for the problem. Here, each particle moves toward the optimum value considering three factors. These factors are current velocity, previous experiences and neighbors' experiences [19].

In a n-dimensional search space, the position and the velocity of the i^{th} particle are determined by $X_i = (X_{i1}, X_{i2}, \dots X_{in})$ and $V_i = (V_{i1}, V_{i2}, \dots V_{in})$ vectors, respectively. $(P_{best} = X_{i1}^p, X_{i2}^p, \cdots, X_{in}^p)$ and $(G_{best} = X_{i1}^G, X_{i2}^G, \cdots, X_{in}^G)$ represent the best position of the i^{th} particle and its neighbor respectively. The corrected velocity and the position of each particle at the end of any iteration are given:

$$\begin{aligned} V_i^{k+1} = \omega V_i^k + c_1 . r_1 . (P_{best}^k - X_i^k) + \\ c_2 . r_2 . (G_{best}^k - X_i^k) \end{aligned} \tag{18}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{19}$$

where, V_i^k is the velocity of the i^{th} particle in the k^{th} iteration, ω represents the weight inertia factor, and c_1 and c_2 are the acceleration coefficients. The parameters r_1 and r_2 are random numbers within [0 1] and X_i^k shows the position of the i^{th} particle in the k^{th} iteration.

During the updating process of the velocity, the values of parameters such as ω should be determined in a progressive form. Generally, in order to increase the convergence feature, the weight inertia (ω) is updated in a way that it linearly decreases and in each iteration has same weight for all population [12].

3.2. A review on PSO-SIF algorithm

In the PSO-SIF, each population has its own inertia factor changing with the feedback from best obtained cost in the range [0.3, 0.9]. In this state, decline of the inertia factor and the search space of algorithm are prevented by increasing the iterations.

In the proposed algorithm, the minimum inertia factor is selected to be 0.3, resulting in a situation in which the populations have the costs near the optimum global cost, searching over an optimal point with lower velocities.

In the proposed algorithm, the smart inertia factor is determined by Eq. (20):

$$\omega_j = \frac{0.6 \times (\lambda_j - 1)}{\delta_{\mathrm{m}}} + 0.3 \tag{20}$$

$$\lambda_j = \frac{\mathrm{cost}_j}{\mathrm{cost}_{gbest}} \tag{21}$$

$$\delta_{\mathrm{m}} = \delta_1 - (\frac{iter}{iter_{\max}}) \times \delta_2 \tag{22}$$

where, $cost_j$ is j^{th} population cost, $cost_{gbest}$ refers to the best group cost; λ_j is j^{th} population cost ratio to the cost of the best group solution; and δ_m refers to cost variation percent of j^{th} population from the best group solution rate. *iter* is program iteration number; $iter_{max}$ refers to the most number of program iteration; and δ_1 , δ_2 are the adjustment parameters of this algorithm.

The program implementation process through the PSO-SIF technique is summarized as follows:

Step 1: Algorithm initialization,

Step 2: Randomly initial population and particle's initial velocity generation,

Step 3: CEDR problem cost calculation and costs sorting and selecting P_{best} and G_{best}.

Step 5: Calculation of ω_j for each population according to Eq. (20),

Step 4: Updating particles velocity according to Eqs. (18) and (19),

Step 5: Correcting the new positions of the particles to satisfy the constraints of the problem,

Step 6: Go to the third step until the problem's ending criterion was not satisfied,

Step 7: Extracting the best cost's values of each function from the per unit form after program implementation ending; The best values correspond-ding to the best cost amount, which is the best position of particles (G_{best}) or the best arrangement of units power generation depicted initially are applied in Eqs. (2) and (7) to calculate the optimum system fuel and emission cost in terms of ($/h). In continuous, it is applied in Eq. (10) to obtain system optimum EENS in terms of (MWh).

4. NUMERICAL EXPERIMENTATIONS

All the programs are developed and simulated using MATLAB version 7.01. The system configuration is Pentium IV processor with 3.2 GHz speed and 2 GB RAM. In all experimentations, the ED is considered for just one hour. For each case study of the problem, thirty separate experimentations are conducted to be able to compare the solution quality and convergence features. The initial population size and iteration number are 100 and 1000, respectively and, c_1, c_2 are considered as 2.0. The objective function's penalty factor in per unit form is 0.07 and 100 in non-per-unit form.

The proposed method is applied on two systems: 6-unit system considering ED, emission and reliability level and 26-unit system considering ED and reliability level.

4.1. Six units system

Tests are carried out on 6 generating units system with equality and inequality constraints and valve-point effects. The system total load is 1200 MW. The fuel cost coefficients, generator limits and emission factors are reported in [17].

The experimentations are conducted in three separate sections as CEDR problem solving considering different influence percentages of reliability, CEDR problem solving considering different outage rate of power plants and CEDR problem solving considering emission cost.

4.1.1. Solving CEDR problem considering different influence percentages of reliability

Six independent experimentations cases 1 to 6 are conducted considering different influence percentta-ges of each independent function on the objective function to investigate the accurately optimized problem.

In order to calculate the system reliability, it is assumed that the *FOR* values of units in different cases (1 to 6) are shown in Table 1-(A).

It is tried to optimize the economic dispatching in six different experimentations applying different perce-nttages of system reliability. The experimentations are detailed as follows:

1) It is aimed to reduce the unit's fuel costs consid-ering reliability without level. The coefficients

related to the influence percentage of each function in objective function are equal to $\gamma = 1$ and $\mu = 1$.

2) It is aimed to decrease the fuel cost of plants applying 20% reliability level influence in the object-tive function.
3) It is aimed to decrease the fuel cost of plants applying 40% reliability level influence in objective function.
4) It is aimed to decrease the fuel cost of plants applying 50% reliability level influence in objective function.
5) It is aimed to decrease the fuel cost of plants applying 60% reliability level influence in objective function.
6) It is aimed to increase the reliability level without considering fuel cost.

The results of the experimentations are illustrated in Table 2. The parameter TP in Table 2 depicts the total power amount of the system and F represents fitness values in objective function in per unit form. The results of the first experiment are shown in the second column of Table 2. In this experimentation, the ED was accomplished to decrease the optimized system's fuel costs without considering system reliability. The system fuel cost in per unit form is 0.615701 pu, which is the minimum among the other case studies. In this case, the EENS is 46.6279 MW, which is the most and is the worst case in comparison with the other case studies.

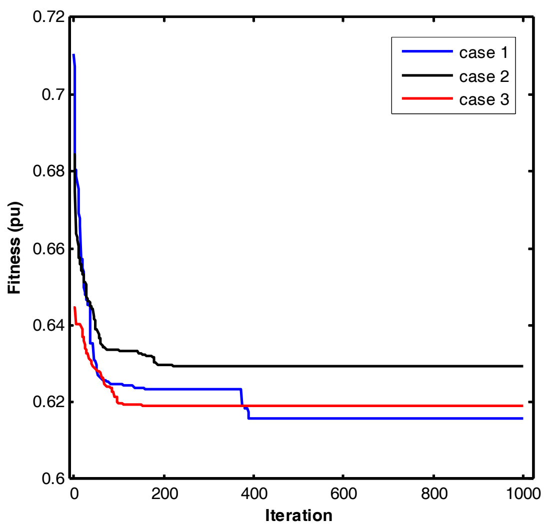

Fig. 1. Convergence characteristics of the PSO-SIFs for test system 1

Comparing the results of the second experiment-tation is shown in the third column of Table 2 depicts that the system EENS value decreases by 5.8503 MWh and reaches to 40.7776 MWh in comparison with the previous case and increases the system reliability influence percentage up to 20% in objective function. It is obvious, as the reliability influence percentage in system objective function increases, the EENS value decreases proportionally and as the fuel cost influence percentage in objective function decreases, its value increases proporti-onally. This is accomplished in a way that as the system reliability influence percentage increases by 40% and the influence percentage of the units fuel cost decreases by 40% in the fourth case study, the EENS value decreases in comparison with the first case by 6.9984 MWh. The notable point in the search algorithm with the objective function in per unit form is its ability to simply detect the best cost with an accuracy equals to the case in which the objective function is not considered in per unit form. In Fig. 1, the convergence characteristics of the CEDR problem' objective function in per-unit form is presented (case studies 1, 2 and 3) optimized through the PSO-SIF algorithm.

4.1.2. Solving EDR Problem Considering Different Outage Rate of Power units

In order to investigate the influence of units outage rate on the amount of power delivered to the system six experimentations are conducted. In all case studies, the aim is to decrease the units' fuel cost considering 50% system reliability influence on objective function. The FOR values for B-G experimentations are shown in Table 1 and are detailed as follows:

A) The outage rates of A stat mode are presented in column 2 of Table 1. These values are applied in all six case studies.
B) The FOR value of unit 1 is increased by 25% in comparison with A case. In other words, $FOR_{B,1} = 1.25 \times FOR_{A,1} = 0.05$.
C) The FOR value of unit 2 is decreased by 57% in comparison with A case.
D) The FOR value of unit 3 is decreased by 40% in comparison with A case.

Table 1. Different forced outage rate values applied in six units system

Case study	A	B	C	D	E	F	G
Unit 1	0.04	0.05	0.04	0.04	0.04	0.04	0.04
Unit 2	0.035	0.035	0.02	0.035	0.035	0.035	0.035
Unit 3	0.05	0.05	0.05	0.02	0.05	0.05	0.05
Unit 4	0.02	0.02	0.02	0.02	0.03	0.02	0.02
Unit 5	0.03	0.03	0.03	0.03	0.03	0.05	0.03
Unit 6	0.04	0.04	0.04	0.04	0.04	0.04	0.02

Table 2. Results of ED in a system with six-generation applying different reliability percentages

Unit Output (MW)	$\gamma = 1.0$ $\mu = 0.0$	$\gamma = 0.8$ $\mu = 0.2$	$\gamma = 0.6$ $\mu = 0.4$	$\gamma = 0.5$ $\mu = 0.5$	$\gamma = 0.4$ $\mu = 0.6$	$\gamma = 0.0$, $\mu = 1.0$
Unit 1	94.7998	94.8074	94.8044	94.7998	94.8000	20.0000
Unit 2	100.0000	26.9860	99.9883	20.0027	99.9865	20.0000
Unit 3	568.7989	419.2013	344.3994	269.5996	120.0013	120.0000
Unit 4	259.5996	508.9365	510.6424	515.9981	510.8098	519.9996
Unit 5	136.8015	110.0686	110.1652	259.5996	334.3979	480.0004
Unit 6	40.0000	40.0000	40.0000	40.0000	40.0000	40.0000
F_{FC}	29491.4289	31191.78	31616.91	32862.8637	34217.1802	35725.7273
EENS	46.6279	40.7776	39.6295	37.6800	35.1399	33.9000
TP	1200	1200	1200	1200	1200	1200
F	0.615701	0.627417	0.618371	0.607280	0.603604	0.622536
RT	1.5765	1.6724	1.6765	1.6761	1.6801	1.3765

*F_{FC} :Fuel Cost [$/h], TP: Total Power [MW], F: Fitness [pu], TC: Total Cost [$/h], RT: Run Time [sec.]

Table 3. CEDR problem results considering different FOR of power units

Unit Output (MW)	A	B	C	D	E	F	G
Unit 1	**94.7998**	**57.3999**	20.0000	94.7998	94.7993	94.7998	20.0001
Unit 2	**20.0027**	20.0021	**100.00**	20.0004	100.0000	100.0000	99.9992
Unit 3	**269.5996**	269.5996	269.5996	**575.8662**	269.5996	344.3994	269.5996
Unit 4	**515.9981**	366.3990	409.1993	359.3328	**409.20000**	510.7999	508.9324
Unit 5	**259.5996**	446.5992	361.2009	110.0007	259.5993	**110.0000**	133.2403
Unit 6	**40.0000**	40.0000	40.0000	40.0000	66.8030	40.0007	**168.2282**
F_{FC}	32862.8637	33531.4483	33435.4890	29716.8443	32565.4949	31616.8925	33706.4957
EENS	37.6800	39.3760	36.9000	28.0960	43.5080	41.82799	35.32038
TP	1200	1200	1200	1200	1200	1200	1200
F	0.607280	0.621957	0.613348	0.573768	0.624306	0.587282	0.614260

Table 4. CEDR problem results considering emission cost

Unit Output (MW)	Minimization of F_c	Minimization of EC	Minimization of $EENS$	Minimization of F_c , EC (TC)	Minimization of F_c , E , $EENS$
Unit 1	94.7998	20.0000	20.0000	20.0006	20.0000
Unit 2	100.0000	20.0000	20.0000	20.0000	20.0000
Unit 3	568.7989	120.0000	120.0000	344.3995	269.5996
Unit 4	259.5996	520.0000	519.9996	515.9995	508.9324
Unit 5	136.8015	479.9995	480.0004	259.6001	341.4675
Unit 6	40.0000	40.0005	40.0000	40.0002	40.0005
F_{FC}	29491.4289	35725.7406	35725.7273	32853.5682	33733.8192
EC	20227.6538	15064.2739	15064.2988	16456.5568	15971.7365
TC	49719.0828	50790.0145	50790.0261	49310.1250	49705.5557
EENS	46.6279	33.9001	33.9000	38.4280	37.0026
TP	1200	1200	1200	1200	1200
F	0.653968	0.475455	0.622536	0.640650	0.6821548

*EC :Emission Cost [$/h], TC: Total Cost [MW],

E) The *FOR* value of unit 4 is increased by 50% in comparison with *A* case.
F) The *FOR* value of unit 5 is increased by 66% in comparison with *A* case.
G) The *FOR* value of unit 6 is decreased by 50% in comparison with *A* case.

The parameter $FOR_{B,1}$ indicates the FOR value of unit 1 in case B, with value equal to 0.05 and is shown in Table 1. The results obtained from A-G experimentations are shown in Table 3.

The experimentations aim to investigate the influence of different values of FOR on each unit's delivered power amount, system fuel cost, and reliability. In experiment *B*, the outage rate of unit 1 is increased by 25% in comparison with case *A*. As a result, the reliability of the unit 1 is decreased. As shown in Table 3, as the outage rate of unit 1 in state *B* increased in comparison with case *A* of the same unit, the amount of delivered power in constant load of 1200 MW decreases from 94.7998 MW to 57.3999 MW. This shows the existence of linear relation between *FOR* and consequently the unit 1 reliability and the power amount delivered to the system. Therefore the total EENS of the system increases from 37.6800 MW in *A* case study to 39.3760 MW in *B* case. This depicts the influence of generated power of a unit on total system EENS.

In case study *C*, the outage rate of unit 2 is decreased by 57% in comparison with that of the case *A*. The decreasing of outage rate results in considerable increasing in unit 2 reliability and generated power amount. As it is shown in Table 3, the generated power of unit 2 increases from 20.0027 MW in case *A* to 100 MW in case *C*. Here, the amount of EENS is decreased in comparison with case *A* as expected.

4.1.3. Solving CEDR problem considering emission cost

Tests are conducted on a system with six generation units considering fuel cost, emission cost and reliability level. The system data for emission is presented in [17]. The aim is minimization of fuel cost, emission cost and the EENS of system.

The simulation results using PSO-SIF are presented in Table 4. In Table 5, the results of solving CEDR problem considering emission cost through PSO-SIF are compared with that of PSO and PSO-TVAC methods. In this comparison, per-unit coding is used to combine the proposed multi-objective problem and offer a single objective function. For PSO, c_1 and c_2 are set to 2.0. The weighting inertia coefficients for both PSO and PSO-TVAC were considered a varying number in the range [0.3, 0.9] and the initial populat-ion size and iteration number are 100 and 1000, respectively. The adjustable parameters for PSO-TVAC algorithm were chosen as: $C_{1f} = C_{2f} = 2.5$ and $C_{1i} = C_{2i} = 0.5$ [11].

Table 5. Comparison of results of each method for CEDR problem considering emission cost

Unit (MW)	Minimization of F_C , ED , $EENS$		
	PSO	PSO-TVAC	PSO-SIF
Unit 1	94.8007	20.4902	20.0000
Unit 2	100.00	20.0180	20.0000
Unit 3	269.5996	269.4790	269.5996
Unit 4	510.7996	445.5142	508.9324
Unit 5	184.7999	404.2935	341.4675
Unit 6	40.0000	40.2070	40.0005
F_{FC}	32427.5813	33926.2194	33733.8192
EC	18174.6878	15980.4931	15971.7365
TC	**50602.2692**	**49906.7125**	**49705.5557**
EENS	**38.1320**	**37.6415**	**37.0026**
TP	1200	1200	1200
F	0.6491588	0.644692	0.6821548

As it is obvious from Table 5, the minimum total cost (fuel and emission cost) obtained using PSO-SIF is 49705.5557 ($/h) and the related EENS] is 37.0026 (Mw/h) that are lower than both total cost and system's EENS obtained through PSO and PSO-TVAC approaches which shows the superiority of the proposed PSO-SIF method over the mentioned techniques.

4.2. 26-unit test system

Tests are conducted on a system with 26 units considering fuel cost and reliability level functions. The system total load is 2430 MW and the generation units' data are available in [20]. Reliability data are presented in Table 6 and adapted from [21]. Test are conducted in three separate parts of fuel cost minimization, EENS minimization, and simultaneous cost and EENS level minimization, the results of which by PSO-SIF method are shown in Table 7.

Table 6. Forced outage rate values applied in 26 units system

Units	FOR	Units	FOR	Units	FOR
Unit 1	0.12	Unit 10	0.02	Unit 19	0.02
Unit 2	0.12	Unit 11	0.02	Unit 20	0.02
Unit 3	0.08	Unit 12	0.04	Unit 21	0.02
Unit 4	0.04	Unit 13	0.04	Unit 22	0.02
Unit 5	0.04	Unit 14	0.04	Unit 23	0.1
Unit 6	0.04	Unit 15	0.05	Unit 24	0.1
Unit 7	0.04	Unit 16	0.05	Unit 25	0.1
Unit 8	0.02	Unit 17	0.05	Unit 26	0.1
Unit 9	0.02	Unit 18	0.02		

Table 7. CEDR problem results in 26 units system

UNIT (MW)	Minimization of F_C	Minimization of $EENS$	Minimization of F_C and $EENS$
Unit 1	399.9995	100.0003	288.8665
Unit 2	399.9981	100.0000	284.5642
Unit 3	350.0000	338.7472	349.9972
Unit 4	155.0000	155.0000	154.9999
Unit 5	155.0000	155.0000	154.9997
Unit 6	154.9998	155.0000	154.9999
Unit 7	155.0000	155.0000	154.9999
Unit 8	75.9998	76.0000	75.9971
Unit 9	75.9992	76.0000	75.9961
Unit 10	75.9999	76.0000	75.9998
Unit 11	75.9975	76.0000	75.9995
Unit 12	47.7311	100.0000	99.9982
Unit 13	40.4191	100.0000	99.9985
Unit 14	33.0057	100.0000	99.9994
Unit 15	68.9500	197.0000	68.9513
Unit 16	68.9500	197.0000	69.0070
Unit 17	68.9500	197.0000	68.9500
Unit 18	2.4000	12.0000	11.9763
Unit 19	2.4000	12.0000	11.9606
Unit 20	2.4000	12.0000	11.8017
Unit 21	2.4000	12.0000	11.9391
Unit 22	2.4000	12.0000	11.9969
Unit 23	4.0000	4.1195	4.0000
Unit 24	4.0000	4.0155	4.0005
Unit 25	4.0000	4.0491	4.0000
Unit 26	4.0000	4.0681	4.0000
TP	2430.0000	2430.0000	2430.0000
F_{FC}	33630.0528	42212.3306	36269.9568
EENS	171.9084	126.3550	152.8301
F	0.674581	0.614477	0.734283
TC	1.9702	1.8207	1.9904

In the PSO-SIF algorithm, selecting optimal values for δ_1 and δ_2 is important and plays a key role in quality of optimization process [12]. The results of solving CEDR problem on 26-unit system in terms of various values for δ_1 and δ_2 after 30 independent testes are given in Table 8 and the optimal values for δ_1 and δ_2 are determined as 0.05 and 0.04, respe-ctively.

Table 8. Determination of δ_1 and δ_2 for PSO-SIF in 26 units system

Case	δ_1	δ_2	Minimum F (pu)	Average F(pu)
1	0.1	0.08	0.811464	0.830021
2	0.09	0.07	0.7910099	0.809265
3	0.08	0.065	0.761201	0.778234
4	0.07	0.055	0.739401	0.742561
5	0.06	0.05	0.735021	0.736198
6	**0.05**	**0.04**	**0.734283**	**0.734285**
7	0.04	0.03	0.735114	0.736601
8	0.03	0.024	0.745243	0.750458
9	0.02	0.016	0.759852	0.772213
10	0.01	0.008	0.774485	0.800049

5. CONCLUSIONS

In this paper, the reliability indices are used to optimize the ED problem and it is solved by considering units reliability. In the proposed problem, it is tried in economic dispatching problem to utilize units with higher reliability in addition to lower fuel cost.

The objective function of the proposed problem consists of three independent fuel cost, emission cost and reliability functions. In order to combine these functions in the objective function, this paper proposed a per-unit coding in a way that each function is converted to per unit form based on their maximum amounts.

The results obtained from the experimentations of the first section depict the efficiency of the per uniting several functions in objective function and show the possibility of combining two or three independent functions in a objective function with desired influence percentage combinations. Thus, it is possible to determine the influence rate of the system reliability in ED problem solution. The results obtained from the experimentations depict the fact that the system tends to utilize power units, which have lower values of FOR or units have higher reliability considering power supplied to system.

Today, the power plants outage and power interruption would cause considerable financial damages, which can be sometimes irrecoverable. Therefore, it is necessary to pay attention to the reliability issue in power systems planning. Since one of the initial efforts in supplying demanded power is system ED, this paper proposes the idea of applying reliability indices in economic dispatching to create more reliability in supplying power until the end of utilization and planning. The ED problem solution including the system reliability can be utilized at least in systems that some units of them have high outage rates because of natural disasters such as flood or earthquakes or due to internal difficulties to minimize system EENS amount by receiving less power from them.

REFERENCES

[1] N. Saman and C. Singh, "Reliability Assessment of Composite Power System Using Genetic Algorithms," Springer, *Computational Intelligence in Reliability Engineering*, vol. 39, pp. 237-286, 2007.

[2] A. K. Vermaa, A. Srividyaa and M. V. Bhatkarb, "A Reliability Based Analysis of Generation/Transmission System Incorporating TCSC Using Fuzzy Set Theory," *Proceedings of the IEEE International Conference on Industrial Technology*, Mumbai, India, pp. 2779-2784, 2006.

[3] D. Elmakias, "Reliability of Generation Systems," *Studies in Computational Intelligence,* vol. 111, pp. 171-238, 2008.

[4] R. Billinton and R. Allan "Reliability Evaluation of Power Systems," Second Edition, New York: Plenum Press, 1996.

[5] W. Qin, P. Wang, X. Han and X. Du, "Reactive Power Aspects in Reliability Assessment of Power Systems," *IEEE Transactions Power Systems*, vol. 26, no. 1, pp. 85-92, 2011.

[6] A. K. Barisal, "Dynamic search space squeezing strategy based intelligent algorithm solutions to economic dispatch with multiple fuels," *International Journal of Electrical Power and Energy Systems*, vol. 45, pp. 50-59, 2013.

[7] N. Ghorbani and E. Babaei, "Exchange Market Algorithm," *Applied Soft Computing*, vol. 19, pp:177-187, 2014.

[8] Y. Zhang, D. W. Gong, N. Geng and X. Sun, "Hybrid bare-bones PSO for dynamic economic dispatch with valve-point effects," *Applied Soft Computing*, vol. 18, pp. 248-260, 2014.

[9] T. Jayabrathi, P. Bahil, H. Ohri, A. Yazdani and V. Ramesh, "A hybrid BFA-PSO algorithm for economic dispatch with valve-point effects," *Front. Energy*, vol. 6, no. 2, pp. 155-163, 2012.

[10] V. Hosseinnezhad and E. Babaei, "Economic load dispatch using θ-PSO," *International Journal of Electrical Power and Energy System,* vol. 49, pp. 160-169, 2013.

[11] B. Mohammadi-Ivatloo, M. Moradi-Dalvand and A. Rabiee, "Combined heat and power economic dispatch problem solution using particle swarm optimization with time varying acceleration coefficients," *Electric power Systems Research*, vol. 95, pp. 9-18, 2013.

[12] N. Ghorbani, S. Vakili, E. Babaei and A. Sakhavati, "Particle Swarm Optimization with Smart Inertia Factor for Solving Nonconvex Economic Load Dispatch Problems," *International Transaction on Electrical Energy System*, vol. 24, pp. 1120-1133, 2014.

[13] J. Kennedy and R. C. Eberhart, "Particle swarm optimization", P*roceedings of the IEEE International Conference on Neural Networks*, pp. 1942-1948, 1995.

[14] J. B. Park, Y. W. Jeong, J. R. Shin and K. Y. Lee, "An Improved Particle Swarm Optimization for Nonconvex Economic Dispatch Problems", *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 156-166, 2010.

[15] H. Khorramdel, B. Khorramdel, M. Tayebi Khorrami and H. Rastegar, "A Multi-Objective Economic Load Dispatch Considering Accessibility of Wind Power with Here-And-Now Approach", *Journal of Operation and Automation in Power Engineering*, vol. 2, no. 1, pp. 49-59, 2014.

[16] A. Hatefi and R. Kazemzadeh, “Intelligent Tuned Harmony Search for Solving Economic Dispatch Problem with Valve-point Effects and Prohibited Operating Zones”, *Journal of Operation and Automation in Power Engineering*, vol. 1, no. 2, pp. 84-95, 2013.

[17] Y. Zhang, F. YAO and H. Ho-Ching-IU, “Sequential quadratic programming particle swarm optimization for wind power system operations considering emissions,” *Journal of Modern Power Systems and Clean Energy*, vol. 1, no. 3, pp. 231-240, 2013.

[18] S. Niioka, A. Kozu. M. Ishimaru and R. Yokoyama, “Supply Reliability Evaluation Method for Deregulated Electric Power Market Considering Customers Uncertainty,” *Proceedings of the International Conference on Power System Technology*, pp. 1782-1786, 2002.

[19] H. Shayeghi and M. Ghasemi, “FACTS Devices Allocation Using a Novel Dedicated Improved PSO for Optimal Operation of Power System,” *Journal of Operation and Automation in Power Engineering*, vol. 1, no. 2, pp. 124-135, 2013.

[20] C. Wang and S.M. Shahidehpour, “Effects of ramp rate limits on unit commitment and economic dispatch,” *IEEE Transactions on Power Systems*, vol. 8, pp. 1341-1350, 1993.

[21] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju and R. Billinton, “A report prepared by the reliability test system task force of the application of probability methods subcommittee,” *IEEE Transactions on Power Systems*, vol. 14, pp. 1010-1020, 1999.