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Utilizing RDPSO Algorithm for Economic-Environmental Load Dispatch Modeling Considering Distributed Energy Resources

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ABSTRACT

There are many factors such as long construction time, high investment cost, and low competition between energy providers to justify penetrating the distributed energy resources (DERs) such as wind turbines (WTs) and demand response programs (DRPs) in power systems. The uncertainties about WTs' power output have increased the complexity of the economic-environmental load dispatch (EELD) problem. Because it is very difficult to predict the output power of wind farms, additional costs are imposed to the EELD problem. The mean amount of wind energy density has been used to define the storage and additional costs in the developed model. In addition, the DRPs have been facing the problem in reduction of cost. Demand response programs have been considered in two approaches; in the first approach, a certain percentage of the buses' load determines the maximum amount of participation of the DRPs and in the second one, a certain capacity of these programs determines the maximum amount of their participation. The efficiency of the developed model has been analyzed by simulation results on multi-area IEEE 118 bus test system. The operational constraints in the test system, including lines limit, supply–demand balance and the generation limit of generators, WTs, and DRPs have been considered in the EELD problem. Multi-objective Random Drift Particle Swarm Optimization (MORDPSO) has been used in this study to analyze the model. The effects of DERs have been analyzed on power loss, voltage profile, and static voltage stability of the test system.

Index Terms—Economic-Environmental Load Dispatch (EELD), MOPSO, wind generations, Demand Response Programs (DRPs), Random Drift Particle Swarm Optimization (RDPSO).

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NOMENCLATURE

n_{DR}	DRP providers' number
n_{cg}	Thermal generators' number
n_{wt}	WTs' number
p_i	*i*th themal generator's power
C_{cg}	Cost function of *i*th thermal generator
$f(pw)$	Wind power's probability density function
P_{vw}	*w*th power plant's power at the *v*th area
V	Number of areas
N_r	Generators' number of the *w*th power plant at the *v*th area
$pen(i)$	d_i
C^{wt}	*i*th WTs' cost function
B_{vkw}	Loss coefficients matrix in *v*th area
B_{00v}	Constant loss coefficients vector of the area v

$P_{vw}^{\min}$	Minimum generation power of *w*th power plant at *v*th area
V	Wind speed
λ	Scale factor
ρ	Air density
T	Time period
$POP(i)$	Current position of the *i*th particle
$P_{DR,i}$	Power of *i*th DRPs
N_r	Generators' number of *w*th power plant at the *v*th area
C^{wp}	Additional cost
C^{wr}	Storage cost
k_{pi}, k_{ri}	Constant values for the *i*th WTs
pw_i	Planned power of the *i*th WT
$\alpha_i, \beta_i, \gamma_i$	Coefficients of pollution function of the *i*th power plant
F_E	Total system pollution
P_{Dv}	Power demand at the *v*th area
P_{Lv}	Power loss at the *v*th area
$a_{vw}, b_{vw}, c_{vw}, d_{vw}, e_{vw}$	Cost coefficients of the *w*th power plant at the *v*th area
$TL_{v,k}$	Active power transmission from area *v* to the area *k*
B_{0vw}	Vector of the loss coefficients in area v
$TL_{v,k}^{\max}$	Maximum active power transmission from area *v* to area *k* and vice versa
$P_{vw}^{\max}$	Maximum power of *w*th power plant at the *v*th area
k	Shape factor
$P(V)$	Speed level's cumulative probability function
Γ	Gamma function
$PBEST(i)$	Best position of the *i*th particle
$REP(h)$	Value obtained from the archive
$Pri_{DR,i}$	Price of *i*th DRPs

I. INTRODUCTION

Due to the benefits offered by distributed energy resources (DERs) such as wind turbines (WTs) and demand response programs (DRPs), these resources expanded rapidly and were included in generation expansion plans [1]. Many studies have already presented the use of DERs in the power system. Utilizing these resources in reducing power losses has been studied in [2, 3]. In these studies, a load shifting has been occurred to reduce the loss. The reliability of the power system has been improved by DRPs in [4, 5]. In other studies, DRPs have been used as spinning reserve resources to minimize the expected energy that was not served and loss of load probability as reliability indices [6, 7]. In [8, 9], the fuel and emission costs have been reduced by incentive-based DR and finally some studies about the utilizing DR in the real cases such as Europe and Hawaii have been presented in [10, 11]. Utilizing WTs in the power systems has also been presented by some studies [12–15].

One of the most important problems in the power system operation is that economic-environmental load dispatch (EELD) has typical objectives including operation and environmental costs minimization [16]. As DERs cause less pollution than traditional power plants, their use has increased with increasing in environmental concerns. However, the power output uncertainties of these resources have increased the EELD problem's complexity in the networks [16]. By considering DERs, the EELD problem might yield different costs is [17, 18].

Many methods have been used to solve the EELD problem [19–21]. The genetic algorithm (GA) and fuzzy logic methods have been used to solve the EELD problem. A modified GA has also been used to solve this problem [22]. PSO [23], ant colony optimization (ACO) [24], modified bacterial foraging (MBF) [25], and differential evolution (DE) [26] are the other algorithms that have been used to solve the EELD problem.

The EELD problem has been also studied in multi-area power systems. In [27], dynamic planning (DP) is used for solving EELD in multi-area networks. Also, neutral network is used for solving this problem in [28]. Multi-fuel nature of generators in multi-area systems was taken into account in the EELD problem [29]. In general, it can be said that wind speed variations would have a significant effect on solving the EELD problem in systems with WTs [30–32]. Innovative contributions of this study are as follows:

- Developing a model for EELD problem considering conventional units and DERs,
- Developing a method for simulating the WTs power,
- Minimizing the EELD problem's objective function using the interior-point approach,
- Utilizing the average wind energy for calculating the storage and additional cost considering wind, DRPs, and thermal generations.
- Utilizing MORDPSO algorithm for solving the EELD problem, and
- Modeling of DRPs in two approaches, which are fully explained in the following sections.

Definition of the problem and the developing of model for multi-area EELD problem have been presented in section II. The DERs modeling and their use in the cost function have been presented in section III. The optimal solution method has been described in section IV. The numerical results are presented in section V and conclusion is presented in section VI.

II. DEFINITION OF THE EELD PROBLEM

The objective function, optimization tools, uncertainty models, and constraints have been described in this section as follows.

A. Objective Functions

The objective function of EELD problem includes pollution and operation costs. Both conventional units and DERs have been considered in this problem. So, we should obtain all amounts of p_i (power of ith thermal unit) and pw_i (power of ith WT) to solve the problem. Equation (1) shows the operation cost:

$$g=\sum_{i=1}^{n_{DR}}P_{DR,i}.Pri_{DR,i}+\sum_{i=1}^{n_{cg}}C_i^{cg}\left(p_i\right)+\sum_{i=1}^{n_{wt}}C_i^{wt}\left(p\omega_i\right)+$$

$$\sum_{i=1}^{n_{wt}}C_i^{wp}\left(p\omega_i^{av}-p\omega_i\right)+\sum_{i=1}^{n_{wt}}C_i^{wr}\left(p\omega_i-p\omega_i^{av}\right) \quad (1)$$

The number of conventional units has been shown by n_{cg}, n_{wt} represents the WTs number and p_i represents the ith conventional unit's active power. Also, n_{DR} , P_{DR}, and Pri_{DR} are the number of DRPs, power of DRPs, and the price of DRPs, respectively. C_{cg} is the ith conventional unit's cost function, which is presented in (2):

$$C^{cg}=\sum_{v=1}^{N_v}\sum_{w=1}^{N_w}a_{vw}+b_{vw}P_{vw}+c_{vw}P_{vw}^2+\left|d_{vw}sin\left[e_{vw}\left(P_{vw}^{min}-P_{vw}\right)\right]\right| \quad (2)$$

where, a_{vw}, b_{vw}, c_{vw}, d_{vw}, and e_{vw} are the wth power plant cost coefficients at the vth area, P_{vw} is the power of wth power plant at the vth area, N_r is the number of units of the wth power plant at the vth area, and V is the areas number. Also, the ith WT cost function has been shown in (3):

$$C_i^{wt}\left(p\omega_i\right)=d_i\cdot p\omega_i \quad (3)$$

d_i is the cost coefficient of ith WT. In this problem, the additional cost (C^{wp}) is the difference between the scheduled and available wind power, and the storage cost (C^{wr}) is the difference between the available and scheduled wind power, which is a part of the expected value of such difference. The objective function can be written as (4):

$$g=g_1+g_2+g_3 \quad (4)$$

where,

$$g_1=\sum_{i=1}^{n_{DR}}P_{DR,i}.Pri_{DR,i}+\sum_{i=1}^{n_{cg}}C_i^{cg}\left(p_i\right)+\sum_{i=1}^{n_{wt}}C_i^{wt}\left(p\omega_i\right) \quad (5)$$

$$g_2=k_{pi}\left(\frac{A}{2}\rho\lambda^3T\left(\frac{k+3}{k}\right)-p\omega\right) \quad (6)$$

k_{pi} is related to the ith WT and is a constant value,

$$g_3=k_{ri}\left(p\omega-\frac{A}{2}\rho\lambda^3T\left(\frac{k+3}{k}\right)\right) \quad (7)$$

k_{ri} is related to the ith WT and is a constant value. The additional cost as well as storage cost have been calculated from (8) to (11):

$$C_i^{wp}\left(p\omega_i^{av}-p\omega_i\right)=k_{pi}E\left(p\omega-p\omega_i\right) \quad (8)$$

E has been calculated by (9):

$$E\left(p\omega-p\omega_i\right)=\int_{p\omega_i}^{p\omega_i^r}\left(p\omega-p\omega_i\right)f\left(p\omega\right)dp\omega \tag{9}$$

$p\omega_i$ is the ith WT planned power. Also, the storage cost has been calculated in the (10):

$$C_i^{wr}\left(p\omega_{i-}p\omega_i^{av}\right)=k_{ri}E\left(p\omega_i-p\omega\right) \tag{10}$$

So, according to (11), E is obtained:

$$E\left(p\omega_i-p\omega\right)=\int_0^{p\omega_i^r}\left(p\omega_i-p\omega\right)f\left(p\omega\right)dp\omega \tag{11}$$

The pollution function of power plants has been presented in (12):

$$F_E=\sum_{i=1}^{n_{cg}}\alpha_i P_{Gi}^2+\beta_i P_{Gi}^2+\gamma_i \tag{12}$$

α_i, β_i, and γ_i represent the coefficients of the pollution function for power plant i, and F_E is the total pollution.

B. Constraints

1) Generation–Consumption Balance

$$\sum_{w=1}^{N_w}P_{vw}=P_{D_v}+P_{L_v}+\sum_{k\neq v}TL_{v,k}-\sum_{i=1}^{n_{DR}}P_{DR,v,i} \quad \forall\ v=1,\ldots,V \tag{13}$$

$$P_{L_v}=\sum_{k=1}^{N_v}\sum_{w=1}^{N_w}P_{vw}B_{vkw}P_{vk}+\sum_{w=1}^{N_w}B_{0_{vw}}P_{vw}+B_{00_v} \tag{14}$$

where, $P_{DR,v,i}$ is the DRPs power at the area v, P_{D_v} is the vth area power demand, P_{L_v} is the loss in the area v, $TL_{v,k}$ is the transmitted power between two areas, B_{vkw} is a matrix to show loss coefficients in area v, $B_{0_{vw}}$ is a loss coefficients vector in area v, and B_{00_v} is a vector of constant loss coefficients of the area v.

2) Transmission Constraints

$$\left|TL_{v,k,t}\right|\leq TL_{v,k}^{max} \tag{15}$$

where, $TL_{v,k}^{max}$ is the transmitted power constraint from area v to the area k.

3) Units Constraint About Active Power

$$P_{vw}^{min}\leq P_{vw}\leq P_{vw}^{max} \quad \forall w=1,\ldots,N_v,\quad \forall\ v=1,\ldots,V, \tag{16}$$

where, P_{vw}^{min} and P_{vw}^{max} indicate the minimum and maximum generation..

4) Bus Voltage Limits

The buses voltage must be within a certain range based on this constraint.

5) Demand response programs' Power Limit

The DRPs power should be lower than its maximum. This maximum is either a certain percentage of the load or a certain capacity;

$$0\leq P_{DR,i}\leq P_{DR,i}^{max} \tag{17}$$

III. WIND SERIES

In this study, the wind speed series has been obtained as (18) [20–21]:

$$P\left(V\right)=\frac{k}{\lambda}\left[\frac{v}{\lambda}\right]^{k-1}\exp\left(-\left[\frac{k}{\lambda}\right]^{k}\right) \tag{18}$$

where, V is the speed of wind, k (factor of shape) and λ (factor of scale) are the parameters of Weibull distribution, too. The relationship between the wind speed and its occurrence probability has been determined below [21]:

$$Y=A\cdot X+B \tag{19}$$

$$Y=\ln\left(-\ln\left(1-P\left(V\right)\right)\right) \tag{20}$$

$$X=\ln V \tag{21}$$

The speed of wind and its cumulative probability function (P(V)) have been represented in (20) and (21), respectively.

$$\lambda=\exp\left(-\frac{B}{A}\right) \tag{22}$$

$$k=A \tag{23}$$

The mean density value of wind energy has been obtained by (24):

$$\frac{P}{A}=\frac{1}{2}\rho\lambda^3\Gamma\left(\frac{k+3}{k}\right) \tag{24}$$

where, air density has been represented by ρ and is equal to 1.255 kg/m^3. Equation (25) also shows the mean density value of wind energy:

$$\frac{E}{A}=\frac{1}{2}\rho\lambda^3\Gamma\left(\frac{k+3}{k}\right)T \tag{25}$$

where, T indicates the time period. The (26) shows the speed of the wind with highest probability of occurrence:

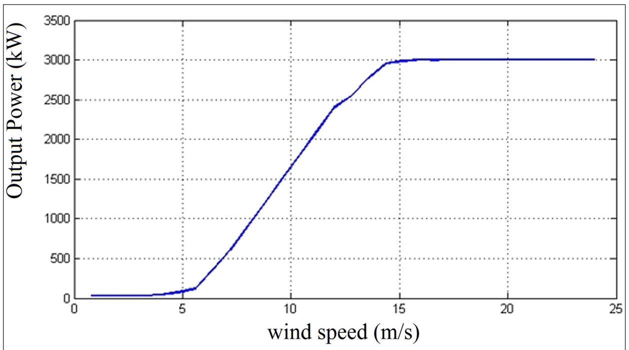

Fig. 1. VESTAS V100 WT curve [23].

$$V_{MP} = C\left(\frac{k-1}{k}\right)^{1/k} \tag{26}$$

Rated wind speed can also be obtained using (27):

$$V_{MaxE} = C\left(1+\frac{2}{k}\right)^{1/k} \tag{27}$$

The power curve typically used to obtain the wind power series from the wind speed is calculated as (28) [16]:

$$pw = \alpha V^3 + \beta V^2 + \gamma V + \delta, \qquad V_i \le V \le V_{i+1} \tag{28}$$

where, the wind power has been shown by pw, wind speed has been indicated by V_j and V_{j+1}, and α, β, γ and δ are the coefficients. The values of VESTAS V100 WT Company's data are shown in Fig. 1.

IV. MULTI-OBJECTIVE RANDOM DRIFT PARTICLE SWARM OPTIMIZATION FOR SOLVING EELD

The theory of random drift particle swarm optimization (RDPSO) algorithm has been presented in [33]. It has been described in nine steps:

Step 1 specifies the generation of each unit and the location of each DRP. The generation of generators and the location of DRPs have been randomly initialized in the search space. Step 2 calculates the wind power series based on (18) to (28) and Fig. 1. Step 3 evaluates the particles fitness functions and gets the best position (local best) and mean best position. Step 4 analyzes each particle to meet the constraints using (13) to (17). The positions must be feasible to satisfy the constraints. Step 5 stores the best local and global positions. Step 6 updates the archive (stores non-dominated positions). In step 7 the non-dominated current positions will be replaced with the particles in the memory. In step 8 the iterations number will be checked. If it reaches the final value, we will go to step 9, otherwise with increase in the generation number we will go to step 3. In step 9, the optimal units generation and the optimal location of DRP providers have been determined, while the power system reaches both the minimum total generation cost and minimum pollutant emission.

V. NUMERICAL RESULTS

A. Problem's Data

The optimization problem has been solved by MORDPSO algorithm. The number of population was 200, and the maximum iteration has been set to 50. Three scenarios have been defined for EELD problem in this study with and without DRPs. Demand response programs have also been considered in two approaches. In the first scenario, minimization of the operation costs is the only objective and in the second scenario, the objective is minimization of pollution. Finally, in the third one, the costs and pollutions were simultaneously supposed to be minimized. In addition, the DRPs have been defined in two approaches. In the first approach, a certain percentage of the buses' load determines the maximum amount of participation of the DRPs and in the second one, a certain capacity of these programs determines the maximum amount of their participation.

The test system has 14 units and 3 areas [34]. The units 1–12 are from thermal. Unit 13 is a wind farm with 40 WTs (VESTAS V80-2.0MW-bus 69), and unit 14 is another wind farm with 25 WTs (VESTAS V90-3.0MW-bus 80). The VESTAS V80 and V90 WTs specifications are shown in Figs. 2 and 3, respectively [23]. The cost function coefficients and the thermal units' generation

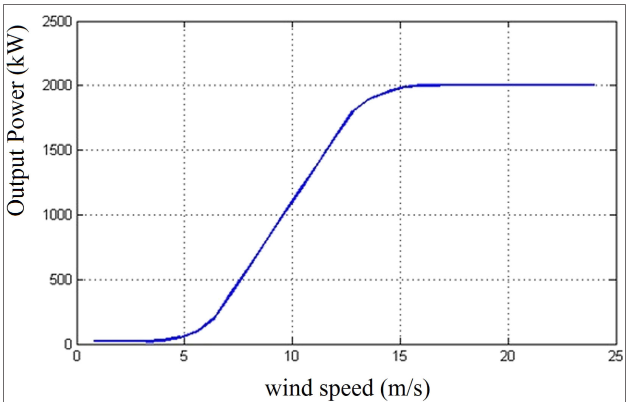

Fig. 2. VESTAS V80 turbines' power curve and operation data [23].

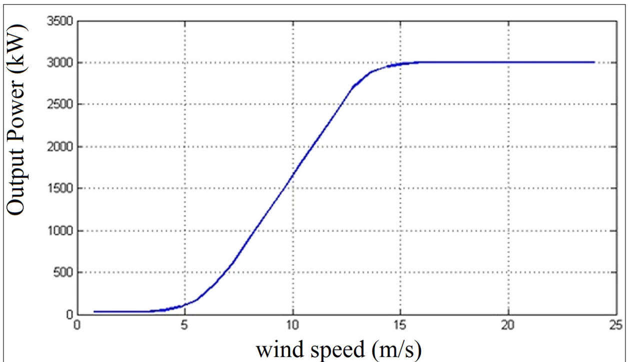

Fig. 3. VESTAS V90 turbines' power curve and operation data [23].

TABLE I. THERMAL UNITS' PARAMETERS [34]

$P_{G\,min}$ (MW)	$P_{G\,max}$ (MW)	γ	B	α	C	B	A	No.
50	300	23.33	−1.5	0.016	0.50	189	150	P_{G1}
50	300	21.02	−1.82	0.031	0.055	200	115	P_{G2}
50	300	22.05	−1.24	0.013	0.60	350	40	P_{G3}
50	300	22.98	−1.35	0.012	0.50	315	122	P_{G4}
50	300	21.31	−1.90	0.020	0.50	305	125	P_{G5}
50	300	21.90	0.80	0.007	0.70	275	70	P_{G6}
50	300	23.00	−1.40	0.015	0.70	345	70	P_{G7}
50	300	24.00	−1.80	0.018	0.70	345	70	P_{G8}
50	300	25.12	−2.00	0.019	0.50	245	130	P_{G9}
50	300	22.90	−1.36	0.012	0.50	245	130	P_{G10}
50	300	27.01	−2.10	0.033	0.55	235	135	P_{G11}
50	300	25.10	−1.80	0.018	0.45	130	200	P_{G12}

limits have been presented in Table I. Also, the WTs cost parameters, including d, k_{pi}, and k_{ri}, are presented in Table II. Moreover, the wind speed parameters are shown in Table III. The data of VESTAS V80 and V90 WTs are shown in Tables IV and V, respectively [23].

B. Economic-Environmental Load Dispatch Problem Without Considering DRPs

1) Economic-environmental load dispatch Problem Without Considering DRPs in the First Scenario

The first scenario results for the proposed strategy (minimizing the operation cost) is presented in Fig. 4. As it can be seen, the operation cost determined was 266 650 \$/h which was reduced. The generation of units and transmitted power between areas have been shown in Fig. 5. Since the objective is costs reduction, a low loading was applied on WTs that had a higher cost.

TABLE II. WIND TURBINE UNITS' COST PARAMETERS [23]

	1	2	3	4	5	6	7	8
D	30	25	35	25	30	25	35	25
k_p	160	160	160	160	160	160	160	160
k_r	200	200	200	200	200	200	200	200

TABLE III. WIND SPEED PARAMETERS [23]

	1	2	3	4	5	6	7	8
λ	8.13	8.24	7.52	9.24	8.11	7.24	7.36	9.09
K	1.99	2.30	2.11	2.41	1.79	2.12	2.03	2.14

TABLE IV. VESTAS V80 DATA [23]

Power Rate	**2000 kW**
Cut-in speed	4 m/s
Wind speed increase rate	16 m/s
Cut-out speed	25 m/s
Rotor diameter	80 m
Rotor sweeper area	5027 m^2

TABLE V. VESTAS 90 TURBINE DATA [23]

Power Rate	**3000 KW**
Cut-in speed	3.5 m/s
Wind speed increase rate	15 m/s
Cut-out speed	25 m/s
Rotor diameter	90 m
Rotor sweeper area	6362 m^2

2) Economic-environmental load dispatch Problem Without Considering DRPs in the Second Scenario

The second scenario results of the proposed strategy (minimizing the environmental pollution) is shown in Fig. 6. The pollution rate of units is 61.16 \$/h, which shows the higher use of WTs.

The active power of generators and power dispatch among areas for this scenario are shown in Fig. 7. The target was to minimize the pollution in this scenario, which necessitated

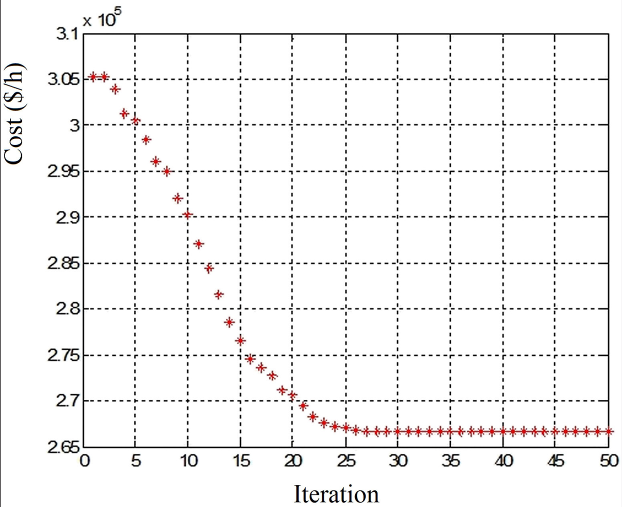

Fig. 4. First scenario results without DRPs.

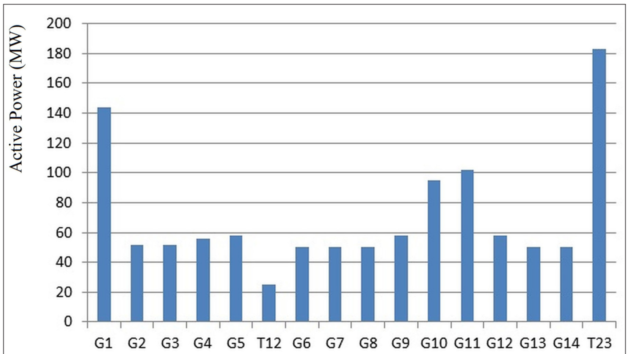

Fig. 5. Active power of generators and power dispatch among areas in the first scenario without DRPs.

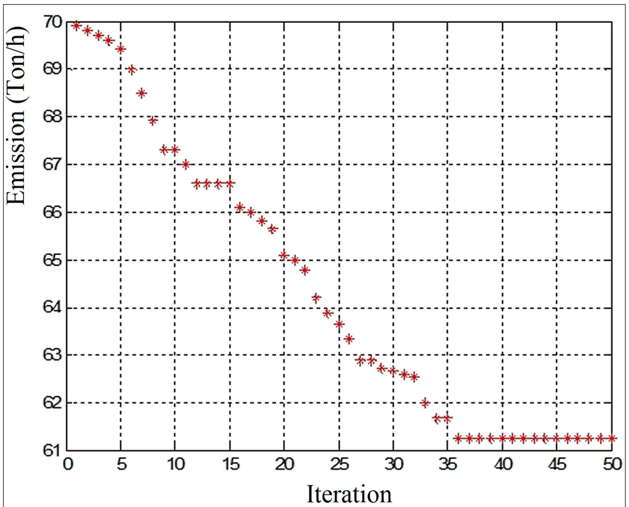

Fig. 6. Results of the proposed strategy for the second scenario (reducing the environmental pollution) without DRPs.

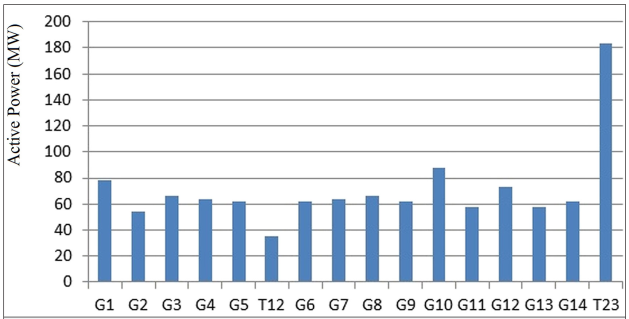

Fig. 7. Active power of generators and power dispatch among areas of test system in scenario 2 without DRPs.

considering the loading on WTs. As shown in Fig. 7, more load is supplied by power plants 13 and 14, which has reduced environmental pollution in this scenario.

3) Economic-environmental load dispatch Problem Without Considering DRPS in the Third Scenario

The two-dimensional results of the developed model have been presented in Fig. 8. The generators power and the transmitted power between areas have been represented in Fig. 9. The objective of this scenario is simultaneously minimization of operation costs and environmental pollutions. The results of this scenario have been presented in Table VI [35]. It also compares the results with three different methods. As can be seen, this table shows the efficiency of the proposed method.

4) Discussion About Economic-Environmental Load Dispatch Problem Without Considering DRPs

Three scenarios were evaluated in this study. The objective is minimization of operation costs and pollution in the first and the second scenarios, respectively. In the third scenario, the goal was to simultaneously minimize both objectives.

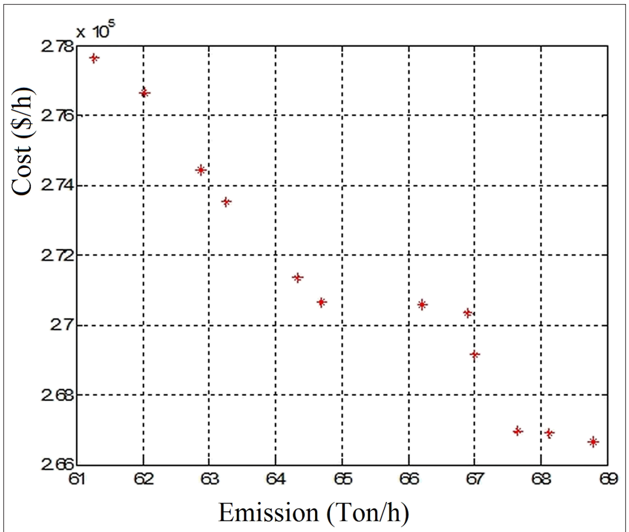

Fig. 8. Two-dimensional Pareto results in the third scenario without DRPs.

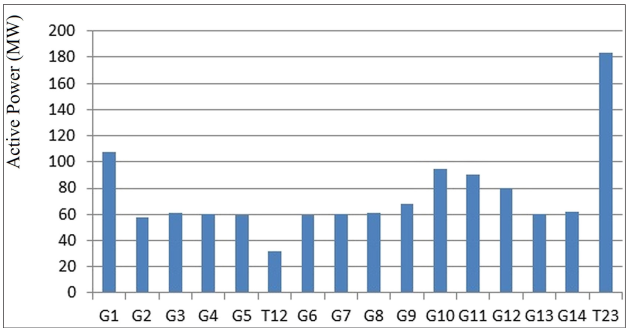

Fig. 9. Active power of generators and power dispatch among areas in scenario 3 without DRPs.

We found that the generators in the area 2 are cheaper than area 1, by comparing the amount of transmitted power from area 1 to 2 in the Figs. 5 and 7; because the transfer power from region 1 to 2 in Fig. 5 was less than in Fig. 7. In addition, by these figures comparison, it is obvious that the generators in the area 1 produce less pollution than generators of area 2, since the transmitted power from area 1 to 2 in Fig. 7 is more than Fig. 5. Also, comparing Figs. 5 and 7, it is clear that wind farm generation is higher when the goal is to reduce environmental pollution. Also, by comparing Figs. 5, 7, and 9, we find that power plant generation is about the average of single-objective scenarios when the problem is considered as two-objective, which shows the accuracy of the proposed method. As the Figs. 4 and 6 show, the convergence rate of the used algorithm is also acceptable, so that it converges in the iterations of 27 and 36 to the optimal solution, respectively.

C. Economic-Environmental Load Dispatch Problem With Considering DRPs

1) Economic-Environmental Load Dispatch Problem With Considering DRPs in the First Approach

In this section, the optimal location and capacity for DRPs are added to the problem variables and finally calculated as the problem outputs. Therefore, in addition to determining the capacity of 12 thermal power plants and two sets of wind units, according to the number of DRPs, location and capacity will be obtained in the network. In this section, the simulation results was calculated in order to determine the optimal location and capacity of the three sets of DRP providers. The maximum limit for the use of DRPs was 10% of the bus load. Therefore, three buses was obtained as the optimal location of DRPs implementation and in each one, a maximum of 10% of the load was reduced by DRP providers. The maximum bid price for these programs was obtained according to the generation price of the last 1 MW by thermal units. Accordingly, in the first to third scenarios, the following results was obtained.

Fig. 10 contains the results of the developed strategy for the first scenario (minimizing the operation costs) in the test systems considering DRPs in the first approach. The operating cost of the thermal units is 222 880 $/h. If the cost paid to DRPs was

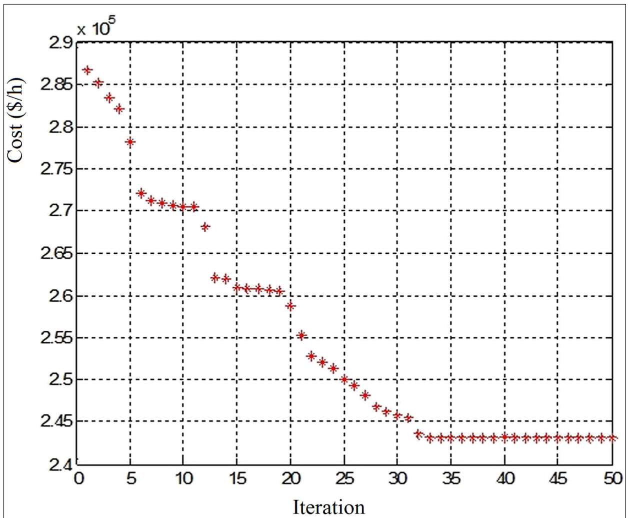

Fig. 10. Results of the proposed strategy for the first scenario with DRPs in the first approach.

TABLE VI. RESULTS OF THE DEVELOPED MODEL FOR THE TEST SYSTEM BY OPTIMIZATION ALGORITHMS

	MORDPSO			**NSGAII [29]**		
Parameters	**Economic dispatch**	**Emission dispatch**	**EELD**	**Economic dispatch**	**Emission dispatch**	**EELD**
Cost($/h)	266650.12	277635.96	270649.3	267850.15	278012.46	270895.6
Emission (ton/h)	68.78	61.16	64.69	68.98	63.48	67.12
	NPGA [35]			SPEA [35]		
Parameters	**Economic dispatch**	**Emission dispatch**	**EELD**	**Economic dispatch**	**Emission dispatch**	**EELD**
Cost($/h)	268510.89	280035.12	272141.1	268111.74	279212.87	271981.4
Emission (ton/h)	70.03	65.55	67.47	72.88	67.44	70.98

MORDPSO, multi-objective random drift particle swarm optimization,

TABLE VII. THE RESULTS OF DRPS IMPLEMENTATION IN THE FIRST APPROACH

DRP Providers	Optimal Location	Optimal Capacity (MW)	Optimal Percent From Load Bus (%)	Maximum Bid Proposed to DRPs ($/h)
Provider 1	59	27.7	10	390
Provider 2	80	13	10	390
Provider 3	54	11.3	10	390

in accordance with the price of the last 1 MW by thermal units, the total operating costs of thermal units and DRPs would be 243 160 $ per hour, which was 23 490 $/h less than in the first scenario without considering DRPs. The results of DRPs implementation are also shown in Table VII. As it can be seen from the results of Table VII, these three DRPs reduced the total network load by 52 MW.

The generated power and transmitted power between the areas are presented in Fig. 11. As it can be seen in this figure, the generation of units 3, 7 and 8 has been reduced, which are more expensive and are located in areas 1, 2 and 2, respectively. The reduced generation of these units has been replaced by DRPs. Since DRPs have been fully implemented in the second area and the generation of units in areas 1 and 2 has been reduced, the transmission capacity has been reduced from area 1 to 2 and the transmission capacity has not changed from area two to three. The reduction in transmission power from area one to two is equal to the reduced generation by unit three, which is located in zone one. The generation of unit three has been reduced by 18 MW and the generation of units seven and eight has also been reduced by 17 MW. On the other hand, the amount of power generation by other units except of these units has also remained unchanged. Fig. 11 also shows the generation amount of units and transmission capacity between areas. The contents described above are reflected in this figure.

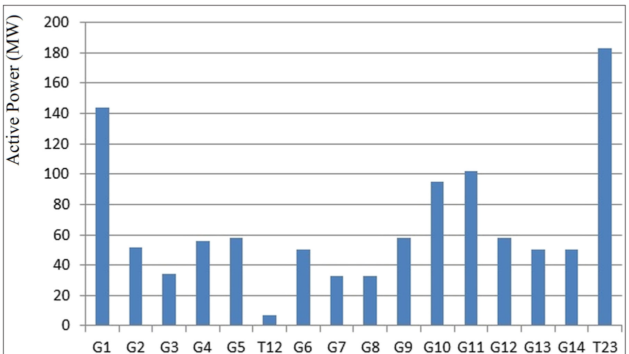

Fig. 11. Power of generators and power transmitted between areas in scenario 1 with DRPs in the first approach.

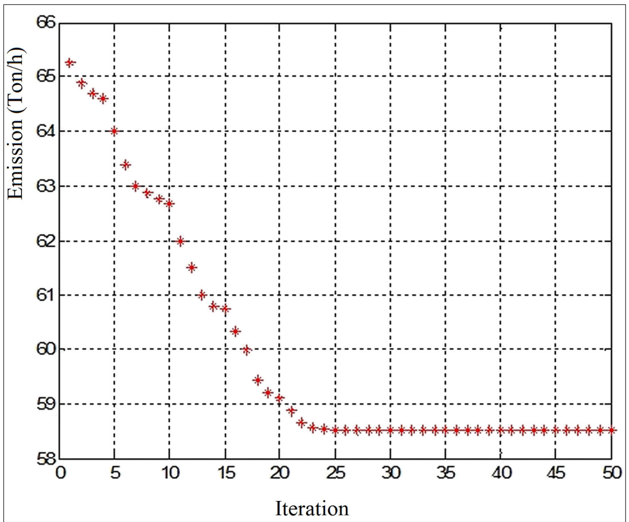

Fig. 12. Results of the proposed strategy for the second scenario with DRPs in the first approach.

The results of the developed strategy for the second scenario with DRPs are shown in Fig. 12. As it can be seen, the amount of generated pollution by units has reached to 58.53 tons per hour. By DRP implementation according to Table VII, the network load will be reduced by 52 MW. This amount of load reduction has been reduced from the generation of more polluting power plants, that contains power plants 1 and 11 (30 MW from the generation of unit 1 and 22 MW from the unit 11). By reducing the generation of these units to the levels mentioned in previous, the amount of network pollutants has decreased by 2.73 tons per hour. According to the results of Table VII, DRPs in this section have also implemented in the bus with the highest amount of load, because due to the limited participation of 10% of the bus load, DRP providers can have the highest performance in these buses.

Fig. 13 shows the active power of the units and the power transmitted between the areas for the second scenario considering DRPs in the first approach. As mentioned before, the

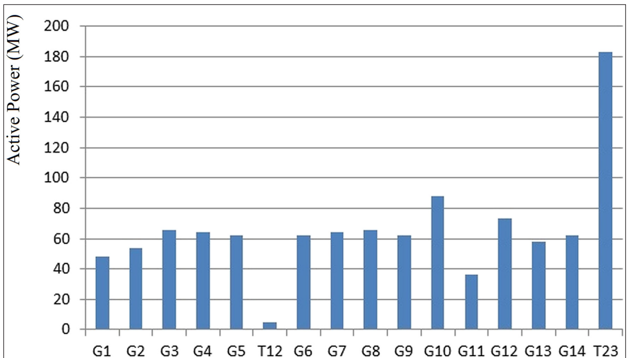

Fig. 13. Power of generators and power transmitted between areas in scenario 2 with DRPs in the first approach.

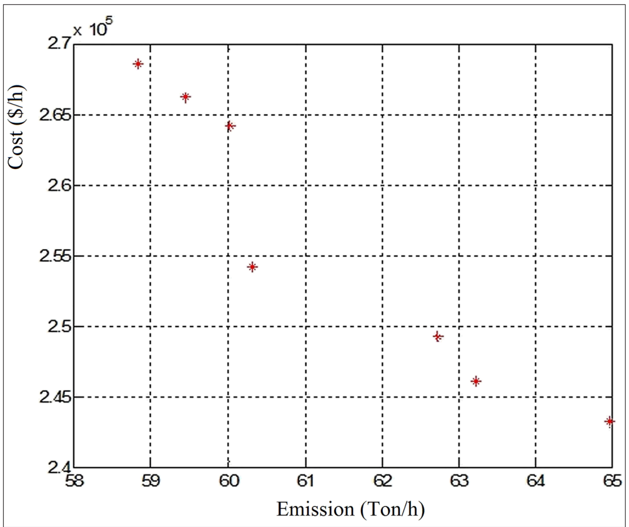

Fig. 14. Results of the proposed strategy for the third scenario with DRPs in the first approach.

generation of units 1 and 11 have been reduced. Therefore, the transmission power from area 1 to 2 has been reduced as much as the generation of unit 1 (30 MW).

Two-objective optimization in this section has been done using MOPSO algorithm. The simulation results of this section are shown in Fig. 14. As mentioned before, all Pareto front answers are optimal that have one strength and one weakness in comparison to each other. Therefore, each of these points can be selected as the optimal point. The network operator selects one of these points according to the expectations from the operation cost and pollution.

The generated active power of units and the power transmitted between the areas for the third scenario are shown in Fig. 15 considering the DRPs implementation. In this scenario, the goal was to reduce operating costs and environmental pollution simultaneously. Table VIII shows the definite results of the proposed method in two cases with and without the use of DRPs. As it can be seen from the results of this table, the amount of objective functions has improved by the usage of DRPs.

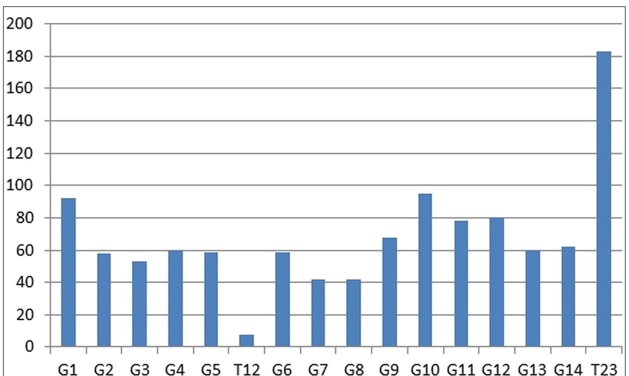

Fig. 15. Power of generators and power transmitted between areas in scenario 3 with DRPs in the first approach.

2) Economic-Environmental Load Dispatch Problem With Considering Demand Response Programs in the Second Approach

In this section, the limit of using DRPs has been changed from a certain percentage of bus loads to a certain capacity of bus load. The maximum criterion for DRPs implementation in this section is 10 MW, which almost all buses had the potential to provide. The results of DRPs implementation with such a criterion were obtained according to Table IX. In the previous section, the buses were obtained as the optimal location for DRPs implementation that had the highest load, but since in this section a certain percentage of bus load is not considered and there is a maximum of 10 MW for DRPs implementation, the buses are selected as the optimal location in Table IX that have the greatest possible distance from the units. This is because reducing the load in the far areas will lead to a greater reduction in losses and a greater reduction in operating costs and environmental pollution. Therefore, the reduction of load in the buses 112, 86, and 90 led to a further reduction in power losses, and consequently the objective functions of the problem were further improved. In all the three scenarios in this approach, these locations were obtained as the optimal locations.

3) Discussion About Economic-Environmental Load Dispatch Problem With Considering Demand Response Programs

The results of this section can be compared in two different ways. In the first case, we compare the results of these three scenarios with each other. By comparing the simulation results in this section, we achieve the same results as the non-use of DRPs. In other words, in the first scenario, the transmitted power from the first area to the second area is less than the second scenario. This reveals that second area thermal units are cheaper than first area units, while the first area units are less polluting than second area units. In addition, in the second scenario, more wind units are used because these units do not cause environmental pollution.

However, comparing the results of these three scenarios in the use and non-use of DRPs, it can be said that the use of DRPs will reduce both operating costs and the amount of environmental pollution. The reason for the reduction in operating cost is that the amount paid to the DRPs is equal to the most expensive units when the generation target is 52 MW less than the load when DRPs are not used. Therefore, since the generation costs of units are upward, the proposed price to DRPs will be less than the last megawatt generated by thermal units in the absence of DRPs. In other words, the maximum price offered to DRPs is equal to the generation cost of 52 MW less than the maximum generation of thermal units in the absence of DRPs. On the other hand, since the reduction in load means a reduction in the generation of thermal units, the environmental pollutants will naturally be reduced.

TABLE VIII. THE RESULTS OF THE PROPOSED METHOD IN 3 SCENARIOS WITH AND WITHOUT CONSIDERING DRPS IN THE FIRST APPROACH

	With DRPs			Without DRPs		
Scenarios	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Cost ($/h)	243160.44	268512.54	254188.65	266650.12	277635.96	270649.32
Pollution (Ton/h)	64.98	58.83	60.32	68.78	61.26	64.69

TABLE IX. THE RESULTS OF PROPOSED METHOD IN ALL THREE SCENARIOS WITH CONSIDERING DRPS IN THE SECOND APPROACH

	Optimal Location	**Optimal Capacity (MW)**
DRP provider 1	112	10
DRP provider 2	86	10
DRP provider 3	90	10

The limiting factor of DRPs implementation in the first approach was a certain percentage of the buses load. This specific percentage was considered 10%. Due to the definition of such a limiting factor, naturally the buses were obtained for DRPs implementation that had a higher load. Because when a bus had a higher load it led to a higher implementation of DRPs and the benefits of implementation was more.

However, the load limit was changed from a certain percentage of bus load to a certain capacity, to evaluate which bus was an optimal place to use DRPs in equal capacity conditions. The maximum criterion for the use of DRPs in this case was considered to be 10 MW; that almost all buses had the potential to implement such a capacity. Since no specific percentage of bus load was considered in this section and there was a maximum of 10 MW for DRPs implementation, buses were obtained as the optimal location that had the greatest possible distance from generation units. This is because, reducing the load in the far areas would lead to a greater reduction in losses and a greater reduction in operating costs and environmental pollution. Therefore, the reduction of load in the buses 112, 86, and 90 led to a further reduction in power losses, and consequently the objective functions of the problem were further improved. In all three scenarios in this approach, these locations were obtained as the optimal locations.

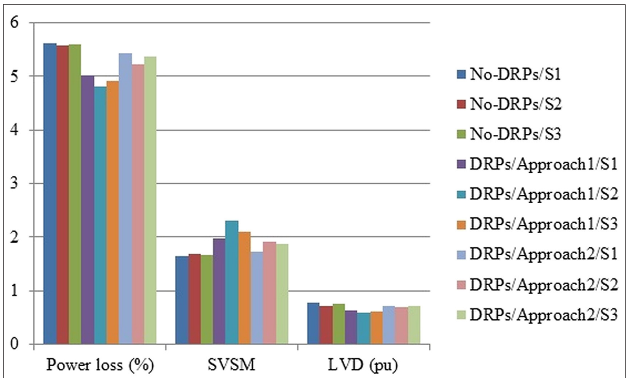

Fig. 16. Power loss, SVSM and LVD in three scenarios with and without DRPs.

Now, to analyze the effects of DRPs implementation on the three important functions of power system such as power loss, static voltage stability margin (SVSM) and load voltage deviation (LVD), we calculate the amount of these functions with and without the DRPs in three scenarios. The result has been presented in Fig. 16 and Table X. These functions formula has been presented in [36]. Based on this reference, the higher amount of SVSM is better as well as the lower amount of power loss and LVD. Based on the Fig. 16 and Table X, better amount of these functions has happened for the first approach of DRPs implementation, because a higher amount of DRPs had been implemented in this approach. Demand response programs implementation in the second approach had been located in the second priority and no-DRPs implementation had been located in the third priority. So, a higher DRPs implementation would lead to a better amount of these three functions in the three scenarios that wass another merit of DRPs implementation.

VI. CONCLUSION

In this study, the EELD problem, which aims to minimize the cost of operation and pollution caused by power plants, was raised. To model this problem, the method of combining objective functions was used, after which the problem was solved using MOPSO. In order to evaluate the effectiveness of the proposed method, numerical studies were performed and the results were compared with various existing methods. The results showed superiority of MOPSO method over other existing methods, and showed that the proposed optimization algorithm has high speed and accuracy in solving this problem.

Further DRPs was added to the problem's model and the simulation results were presented and analyzed using such resources. The simulation results showed that the use of DRPs would simultaneously reduce the operating costs and environmental pollutants. In this study these resources were used in two approaches. In the first approach, the limiting factor for the use of these resources was a certain percentage of the bus

TABLE X. POWER LOSS, SVSM AND LVD IN THREE SCENARIOS WITH AND WITHOUT DRPS

	Scenarios	Power Loss (%)	SVSM	LVD (pu)
No-DRPs implementation	S1	5.6125	1.6532	0.7843
	S2	5.5870	1.6812	0.7123
	S3	5.6011	1.6717	0.7523
DRPs implementation in the first approach	S1	5.0123	1.9654	0.6334
	S2	4.8132	2.3120	0.5923
	S3	4.9221	2.1065	0.6145
DRPs implementation in the second approach	S1	5.4320	1.7234	0.7213
	S2	5.2237	1.9123	0.6832
	S3	5.3654	1.8654	0.7031

load, which led the optimal bus to use these resources with a higher load. In the second approach, the limiting factor of the use of DRPs was considered to be a certain limit of load capacity. In this approach, the optimal buses were shifted to buses farther away from the units because by reducing the load of these buses, the network losses were reduced and the objective functions of the problem were further improved. Also, the DRPs implementation effect has been analyzed on the three important functions of power system such as power loss, SVSM, and LVD; that presented another merit of DRPs implementation.

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