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Hybrid Optimization Method for Thermal-Wind Integration with Multi Objective Dynamic Economic Dispatch

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Abstract

A large electric power system requires an interconnection process to maintain the continuity of electricity service and lighten the burden of the existing power station in the system. In the electrical energy distribution process of the thermal power plant to the load center, a minimum operation cost is required. In this paper, the FOA-ABC hybrid optimization method is proposed to get the best solution from multiobjective dynamic economic dispatch (MDED) in an electrical power system for five tested objective functions by reviewing the power balanced, power limits of the generator, and the generator ramp rate as constraints. The test is done by using three different electrical systems, namely thermal-wind integration of the 26 bus IEEE system that was carried out in two test stages with two functions of objective, the 30 bus IEEE thermal power plant system that also is carried out in two test stages with three and five objective functions, and the Sulselbar thermal power plant real system in Indonesia with two objective functions. Simulation results of the FOA-ABC hybrid optimization method for thermal-wind integration of the 26 bus IEEE system, the 30 bus IEEE system, and the Sulselbar thermal power plant real system compared with the existing another method. It showed that the FOA-ABC hybrid optimization method able to solve multiobjective dynamic economic dispatch problems better with smaller value than the other methods that are being compared. Besides that, the wind power plant integration into thermal power plants can reduce the total operating costs of power plants in an interconnected system.

Keywords: *Hybrid optimization method; multiobjective; dynamic economic dispatch; objective function; thermal-wind integration*

1. Introduction

Power plants in Indonesia are still dominated by thermal power plants including coal power plants, and in the combustion process produce electrical energy, ash, and smoke [1]. The interconnected thermal power plants operate by using fossil fuels with large electricity production cost. Therefore, one of the substantial operations in the power system is minimizing the operating costs of the thermal plant by doing economic dispatch (ED). ED is an optimal output determination of several electric power plants to fulfill the demand of load with the lowest cost. Meanwhile, the DED is dispatching that able to predict load capabilities for a certain period and load changing coordinating by response rate of generator unit.

ELD is one of the substantial management in the electric power systems to optimize generation power that formulated as a problem of non-linear programming [2]. Likewise, the ED is how to get minimum fuel costs from thermal power plants [3].To do the ED, it is necessary to analyze the objective functions that will be optimized. The function of the objective is defined to minimize the generation cost total of thermal plants with optimal generation power for equality and inequality constraints [4].

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Some previous studies related to optimization methods for economic dispatch problems such as chaotic PSO [5], evolutionary programming techniques [6], multi-objective differential evolution with two objective functions [7], evolutionary algorithms [8], improved local search involving bee colony optimization using lambda iteration combined with a golden section search method [9], an efficient meta heuristic algorithm [10], multiobjective fruit fly optimization algorithm with three objective functions [11], firefly algorithm [12], multi-objective harmony search algorithm with two objective functions [13], fuzzified artificial bee colony algorithm with three objective functions [14], a novel method with across neighborhood search [15], MO-FOA with two objective functions [16], simulated annealing algorithm [17], assessment of hurricane versus sine- cosine optimization with two objective functions [18], flower pollination algorithm with two objective functions [19], a chaotic krill herd algorithm with one objective function [20], hybrid with cross-entropy method and sequential quadratic programming with one objective function [21], variable scaling hybrid differential evolution with one objective function [22], hybrid particle multi-swarm optimization with one objective function [23], hybrid PSO-TLBO optimization technique with one objective function [24], new hybrid ICA- PSO approach with one objective function [25], novel hybrid differential evolution algorithm with one objective function [26].

Several studies about optimization methods for ED problems related to thermal-wind integration such as Jaya algorithm with one objective function [27], bat algorithm with one objective function [28], plant growth simulation algorithm with two objective functions [29], gravitational search algorithm with one objective function [30], GSOMP algorithm with two objective functions [31], improved harmony search algorithm with two objective functions [32], cuckoo search algorithm with one objective function [33], BH, BBO and DE algorithm with one objective function [34], PSO algorithm with one objective function [35], MTLBO algorithm [36].

In this paper, the FOA-ABC hybrid optimization method is proposed to get the best solution of MDED by reviewing five objective functions, namely transmission power losses (active and reactive), fuel cost, emission index, power reserve margin considering power balanced, power limits and generator ramp rate as constraints for testing of the 30 bus IEEE standard systems. Next testing is done at a real system of Sulselbar thermal power plants in Indonesia considering power limits as a constraint with two objective functions, namely active power transmission losses, and fuel cost. Meanwhile, the test of thermal-wind integration is done at the 26 bus IEEE systems considering power balanced and power limits as constraints with two objective functions, namely power losses, and fuel cost. All test is compared with the existing other methods.

2. Mathematical Description of The Objective Function

The function of the objective is an objective system that is presented as a decision variable function. The function of an objective is related to an optimization approach and problem. A function is intended to be minimized or maximized through an optimization process. In this paper, optimization is done by reviewing some of the objective functions namely fuel cost, power transmission losses (active and reactive), emission index, and reactive power reserve margin.

2.1. Objective Function of Thermal Power Plant

2.1.1. Fuel Cost

The function of fuel cost that was related to thermal power plants has the fuel cost per power output unit of significantly varies with the generator output. The fuel cost interpretation of the *ith* generating unit represents the cost characteristic function from a generating unit for ED problems that were stated as a quadratic function:

Minimize $$F_i P_i = a_i + b_i . P_{Gi} + c_i . P_{Gi}^2 \quad (1)$$

where a_i, b_i, c_i are fuel cost coefficients and P_{Gi} is an output of the actual power of the *ith* generator.

2.1.2. Active Power Transmission Losses

The active power transmission losses in the electric power transmission line needs to be considered. The loss of power amount during transmission must be analyzed and anticipated so that the power losses are still within the permitted limits. Therefore, the 2nd objective function that will be minimized in the MDED problem is active power transmission losses that were stated as:

$$\sum P_i = \sum P_{Gi} - \sum P_{Di} = V_i . \sum_{j=1}^{n} Y_{ij} . V_j . \cos(\delta_i - \delta_j - \theta_{ij}) \quad (2)$$

where P is losses of active power transmission, P_{Gi} is generating power and P_D is load demand, V_i and V_j are voltage in the bus *i* and bus *j*, Y_{ij} is admittance at bus *ij*, δ_i, δ_j and θ_{ij} are angle magnitude at bus *i* and bus *j*.

2.1.3. Reactive Power Transmission Losses

In an electrical power transmission line, the flow reactive power on transmission can affect the power level at the receiving end. Monitoring and regulating the voltage at the receiving end is very important because the voltage level at the receiving end is higher can cause damage to consumer equipment and will result in losses that are considered large quite. The 3rd objective function to be minimized is reactive power transmission losses that can be expressed as:

$$\sum Q_i = \sum Q_{Gi} - \sum Q_{Di} = V_i . \sum_{j=1}^{n} Y_{ij} . V_j . \sin(\delta_i - \delta_j - \theta_{ij}) \quad (3)$$

where Q is reactive power transmission losses, Q_G is reactive power of the generator and Q_D is demand reactive power.

2.1.4. Reactive Power Reserve Margin

Margin of reactive power reserve is a comparison between reactive power transmission losses with maximum reactive power of the generator. The 4th objective function to be maximized is the reactive power reserve margin and distribute reserves between the generator and SVC proportionally that can be written as:

minimize $$F = \sum_{i=1}^{N_G} \left[\frac{Q_i^2}{Q_{max}} \right] \quad (4)$$

where F is a symbol of the reactive power reserve margin, N_G is the amount of the generators, Q_i is the reactive power transmission losses and Q_{max} is the generator maximum reactive power.

2.1.5. Emission Index

The emission or environmental index is index of an environmental perspective that resulted from thermal plant units such as nitrogen oxide (NOx) and sulfur oxide (SOx) that could be modeled separately. The 5th objective function to be minimized is emission index with formulation a quadratic function and exponential that can be written as:

$$\sum E_i(P_{Gi}) = \sum 10^{-2}(\propto_i + \beta_i . P_{Gi} + \gamma_i . P_{Gi}^2) + \zeta_i . \exp(\lambda_i . P_{Gi}) \tag{5}$$

where E_i is emission index, P_{Gi} is the generator power, $\propto_i$, β_i, γ_i, ζ_i, and λ_i are generator emission coefficient.

2.2.Objective Function Of Thermal-Wind Integration

2.2.1. Cost Function of Thermal-Wind System

Costs for the thermal-wind integration systems consist of fuel costs for thermal units and direct costs, penalty costs, reserve costs for a wind farm that can be written as in Equation 6 [29].

$$C(T, W) = \sum_{i=1}^{M} FC + \sum_{j=1}^{N} WC \tag{6}$$

$$FC = a_i + b_i . P_i + c_i . P_i^2 \tag{7}$$

$$WC = C_{d,j} + C_{p,j} + C_{r,j} \tag{8}$$

where $C(T, W)$ is the thermal units cost total and wind farm, FC is thermal units fuel cost, WC is wind cost for the wind farm, a_i, b_i, c_i are the generator cost coefficients, $C_{d,j}$ is the wind farm direct cost, $C_{p,j}$ is the wind farm penalty cost, and $C_{r,j}$ is the wind farm reserve cost.

2.2.2. Direct Cost of Wind Farm

The wind farm direct costs are linear with the generated power by the wind farm and the function of cost can be expressed as:

$$C_{d,j} = d_j . W_j \tag{9}$$

where d_j is the coefficient of direct cost for wind farm

2.2.3. Penalty Cost for Wind Farm

The cost of penalty is happening due to underestimation of the forecasted wind farm so more than expected that can be expressed as[29]:

$$C_{p,j} = k_{p,j}(W_{j,a} - W_j) \tag{10}$$

$$= k_{p,j} \int_{w_j}^{w_{r,j}} (w - w_j) f_w(w) dw \tag{11}$$

where $k_{p,j}$ is the penalty cost coefficient of the i^{th} wind farm, $W_{j,a}$ is wind power of generation, and $f_w(w)$ is the probability density function of wind power output.

For a single wind farm, the rated wind power capacity (w_r) is analyzed for underestimation of wind power that can be expressed as [29]:

$$C_{pw,j} = k_{p,j}(W_1 - w_1) = s_1 + s_2 \quad (12)$$

$$s_1 = w_1 P(W_1 = w_r)$$

$$= w_1 \left\{ exp\left(-\left(\frac{v_i}{c}\right)^k\right) - exp\left(-\left(\frac{v_o}{c}\right)^k\right) \right\} \quad (13)$$

$$s_2 = \int_{w_1}^{w_r} (w - w_1)\, f_w(w) dw \quad (14)$$

Meanwhile, the function of probability density of wind power output $f_w(w)$ is expressed as in equation 15 [29].

$$f_w(w) = \frac{khv_i}{w_r c} \left(\frac{\left(1 + \frac{hw}{w_r}\right) v_i}{c} \right)^{k-1} exp\left(-\left(\frac{\left(1 + \frac{hw}{w_r}\right) v_i}{c} \right)^k \right) \quad (15)$$

where $h = \left(\frac{v_r}{v_i} - 1\right)$ is the linear range ratio of wind speed to cut-in wind speed.

2.2.4. Reserve Cost for Wind Farm

Reserve costs occur due to lack of wind power, the consequence of wind speed is less than is predicted so utility operators need to provide power to consumers. The formulation of reserve cost for wind farm can be expressed as:

$$C_{r,j} = k_{r,j}(W_j - W_{j,a})$$

$$= k_{r,j} \int_0^{w_1} (w_j - w) f_w(w) dw \quad (16)$$

where $k_{r,j}$ is the reserve cost coefficient for the i^{th} wind farm. While a single wind farm, the rated capacity w_r is analyzed for overestimation of wind power that can be expressed as [29]:

$$C_{rw} = k_r(w_1 - W_1) = s_3 + s_4 \quad (17)$$

$$s_3 = w_1 P(W_1 = 0)$$

$$= w_1 \left\{ 1 - exp\left(-\left(\frac{v_i}{c}\right)^k\right) + exp\left(-\left(\frac{v_o}{c}\right)^k\right) \right\} \quad (18)$$

$$s_4 = \int_0^{w_1} (w_1 - w)\, f_w(w) dw \quad (19)$$

3. DESCRIPTION OF CONSTRAINTS

The generation power of each thermal power plant and wind power plant in a network must be no less or more than the generator minimum and maximum capacity and it's inequality constraints can be expressed as in Equation 20 and 21. Besides that, it needs to be considered the total of generation power must comply with the load demand total plus power transmission losses as shown in Equation 22.

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \quad \text{for} \quad \text{i=1,2,...,} \quad N_G \quad (20)$$

$$0 < w_j \leq w_{j,rated} \quad (21)$$

$$\sum_{i=1}^{N_G} P_{Gi} = P_d + P_L$$
(22)

$$P_L = \sum_{i=1}^{N_G} \sum_{j=1}^{N_G} P_{Gi} B_{ij} P_{Gi} + \sum_{i=1}^{N_G} B_{0i} P_{Gi} + B_{00}$$
(23)

where P_{Gi} is the generated power of the i^{th} generator, $P_{Gi,min}$ is the generation power minimum limit and $P_{Gi,max}$ is the generation power maximum limit, N_G is the amount of the generators, w_j is the wind power of forecasted, $w_{j,rated}$ is the rated power capacity of wind power, P_d is the total of load demand, P_L is the power transmission losses, and B_{ij} is loss coefficient or B-coefficients.

For the next constraint, it is the generator ramp rate that can be meant an increase or decrease in power output units per minute and is usually expressed as megawatt per minute (MW/min) or the generator ability to respond to the load change. Thermal units ramp rate limits can be written as:

$$P_{i,t} - P_{i,t-1} \leq RU_i$$
(24)

$$P_{i,t-1} - P_{i,t} \leq RD_i$$
(25)

where $P_{i,t-1}$ is the i^{th} generator output at time *t-1*, RD_i and $RU_i$is the descending or ascending rate value of the i^{th} generator.

4. DESCRIPTION OF THE FOA-ABC HYBRID OPTIMIZATION METHOD

This optimization method is a combination of FOA and ABC methods which are included in the category of artificial intelligence methods. The algorithm procedure of FOA can be seen in [37] and ABC in [38]. Next, the algorithm procedure of the FOA-ABC hybrid optimization method can be deciphered in the following steps:

1. Enter the parameters setting of FOA and ABC
2. Determine the X-axis and Y-axis position of FOA
3. Calculate distance and solution of FOA
4. Calculate the objective function using Equation 26.

$fitness(i) = ObjectFunct(sol(i,:))$(26)

5. Get the minimum fitness and its index
6. Find the X-axis and Y-axis minimum fitness
7. Determine the value limits of ABC
8. Calculate the objective function using Equation 27

$Fitness = ObjectFunct(ObjVal)$(27)

9. Reset trial counters of ABC
10. Memorized the ABC best food (GlobalMin, and GlobalParams)
11. Enter into main iterative optimization, start iterative of employed bee phase
12. Calculate probabilities using Equation 28

$prob = (0.9 * Fitness/max(Fitness)) + 0.1$ (28)

13. Entry to iterative onlooker bee phase
14. Memorized the ABC best food source (GlobalMin, and GlobalParams)
15. Entry to scout bee phase
16. Set the food sources that the trial counter exceeds the limit value
17. Entry to FOA iterative process

18. repeat steps 2 to 5
19. If a new value is smaller of the best value. Next, update of the best value
20. Find Smellbest and best of FOA
21. If update the best value of FOA (Smellbest) smaller or equal the best food source of ABC (GlobalMin) and best index of FOA smaller or equal GlobalParams index of ABC, then
22. Determine Smellbest equal with GlobalMin and best index equal with GlobalParams index.

The implementation of the hybrid optimization method in solving MDED is carried out with two scenarios for three cases, the first scenario to the thermal power plant system and the second scenario to the thermal-wind integration system.

The steps of applying the hybrid optimization method for thermal generation are described as follows:

1. Enter parameters of the hybrid method, bus data, line data, generator power limits, ramp rate limits, cost coefficient, and emission
2. Determine the initial position of the hybrid method
3. Enter the Y_{bus} matrix, run Newton Raphson's load flow to calculate fitness function or objective functions
4. Find the minimum cost, the minimum reactive and active power transmission losses, the minimum emission index, the minimum reactive power reserve margin
5. Enter into iterative optimization

Repeat steps 2 to 4, if update the best value (Smellbest) smaller or equal the best food source (GlobalMin), and best index smaller or equal GlobalParams index then Smellbest equal with the GlobalMin and best index equal with GlobalParams index.

Meanwhile, the steps of applying the hybrid optimization method for thermal-wind integration are described as follows:

1. Enter parameters of the hybrid method, cost, generator power limits, coefficient of B, B0 and B00, wind parameters, and total of load demand
2. Determine the initial position of the hybrid method
3. Calculate fitness function or objective functions
4. Find the minimum cost, minimum power losses
5. Enter into optimization iterative

Repeat steps 2 to 4, if update the best value smaller or equal the best food source, and best index smaller or equal GlobalParams index then best value equal with the best food source and best index equal with GlobalParams index.

5. SIMULATION RESULTS

To see the effectiveness of the FOA-ABC hybrid optimization method, it was tested in three different cases, namely the 30 bus IEEE thermal power plants system, the Sulselbar thermal power plant real system, and the thermal-wind integration of the 26 bus IEEE system, to obtain the best solution of the MDED problems. For case 1, the results of simulation of the FOA-ABC hybrid optimization method are compared with [39]. For case 2, the results of simulation of the FOA-ABC hybrid optimization method are compared with [40] and [41]. While case 3, the simulation results of the FOA-ABC hybrid optimization method are compared with [29].

5.1. Case 1: System of IEEE 30 Bus

The test of the 30 bus IEEE system was performed by using data of [39] with five objective functions, namely reactive and active power transmission losses, emission index, fuel cost, and reactive power reserve margins by considering power balanced, power limits of generator, and generator ramp rate as constraints. Next, the data that was related to the power of each generation unit, coefficient of the fuel cost, and emission coefficient of the 30 bus IEEE system can be shown in Table 1 and Table 2.

Table 1. Power Limits of the Generator of the 30 Bus IEEE System

	Generating Units	Minimum Power Limits	Maximum Power Limits
Active power (MW)	P_{G1}	50	200
	P_{G2}	20	80
	P_{G3}	15	50
	P_{G4}	10	35
	P_{G5}	10	30
	P_{G6}	12	40

Table 2. Emission Coefficient and Fuel Cost of the 30 Bus IEEE System

		P_{G1}	P_{G2}	P_{G3}	P_{G4}	P_{G5}	P_{G6}
Cost	a	0	0	0	0	0	0
	b	2.00	1.75	1	3.25	3.00	3.00
	c	3.75e-3	1.75e-2	6.25e-2	8.34e-3	2.5e-2	2.5e-2
Emission	$\propto$	4.091e-2	2.543e-2	4.258e-2	5.426e-2	4.258e-2	0.06131
	β	-5.554e-2	-5.094e-2	-5.094e-2	-3.550e-2	-5.094e-2	-5.555e-2
	γ	6.460e-4	4.586e-4	4.586e-2	3.380e-4	4.586e-4	5.151e-4
	ζ	2.0e-6	1.0e-8	1.0e-8	2.0e-5	1.0e-8	1.0e-7
	λ	2.857e-2	8.000e-2	8.000e-2	2.000e-2	8.000e-2	6.667e-2

In case 1, the test was carried out in two stages. For the 1st stage, the test is done with three objective functions, namely reactive and active power transmission losses, and emissions index. While the 2nd stage, test is carried out by using five objective functions, namely reactive and active power transmission losses, fuel cost, emissions index, and margin of reactive power reserve. The simulation results of the FOA-ABC hybrid optimization method in solving the MDED problem for the 1st stage can be seen in Table 3. The convergence curve for the emission index can be seen in Figure 1 with the computational time of 236.474187 seconds. As for the 2nd stage, the simulation results of the FOA-ABC hybrid optimization method can be seen in Table 4 and the convergence curve of fuel costs total can be seen in Figure 2 with the computational time 438.932959 seconds.

Table 3. Optimization Results of the Hybrid Method for 1st Stage Test

Objective Function	Optimal Value
Active power transmission losses	6.912 MW
Reactive power transmission losses	-8.772 Mvar
Emission index	0.05847 ton/hour

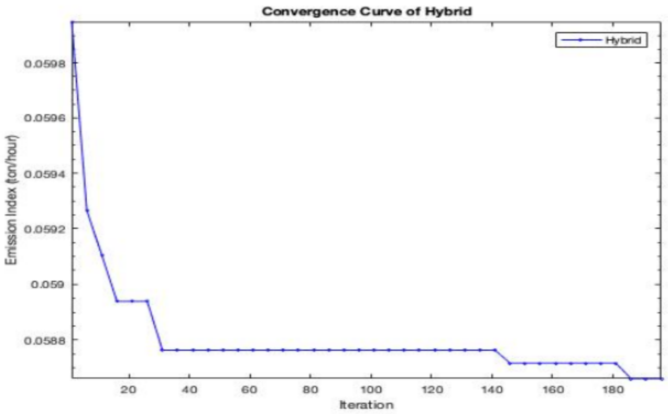

Figure 1. Convergence Curve of Emission Index of the 1st Test Stage for the 30 Bus IEEE System

Table 4. Optimization Results of the Hybrid Method for 2nd Stage Test

Objective Function	Optimal Value
Fuel cost	793.6882 $/hour
Active power transmission losses	6.754 MW
Reactive power transmission losses	-8.985 Mvar
Emission index	0.0697 ton/hour
Reactive power reserve margin	0.21125

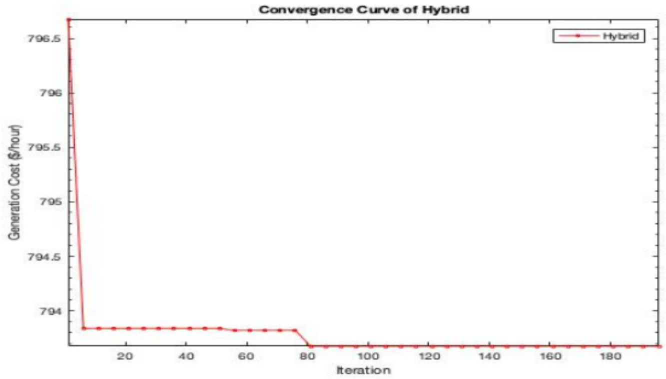

Figure 2. Convergence curve of total fuel cost of the 2nd test stage for the 30 bus IEEE system

5.2.Case 2: Sulselbar Thermal Power Plants Real System

The test data of the Sulselbar thermal power plant real system when peak load is taken from [41] for two objective functions as tested parameters to get the optimal value of the FOA-ABC hybrid optimization method by considering power limits and power balanced as constraints. The diagram of a single line, power limits of the generator, and fuel cost function of the Sulselbar thermal plants can be shown in Figure 3 and Table 5.

The simulation results of the FOA-ABC hybrid optimization method for the Sulselbar thermal power plant real system can be seen in Table 6 and the convergence curve of fuel cost total can be seen in Figure 4 with the computational time of 308.913527 seconds.

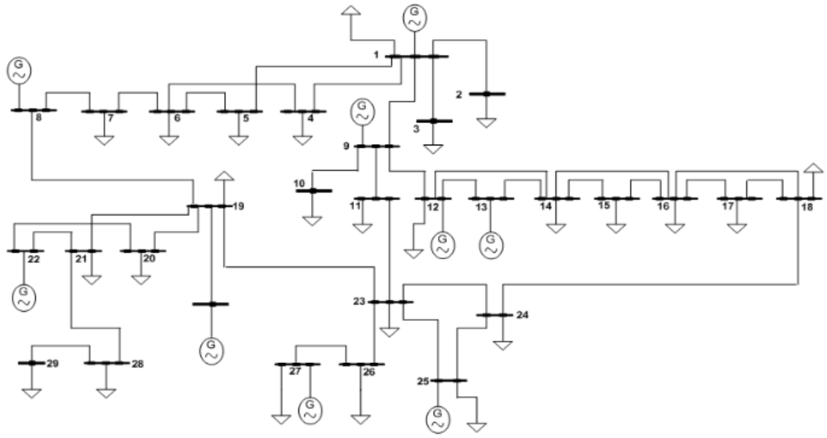

Figure 3. Single line diagram of Sulselbar thermal power plant real system

Table 5. Function of Fuel Cost and Power Limits of the Sulselbar System

Unit	Function of Fuel Cost (IDR/hour)	P_{min}	P_{max}
1	$1.3736e\text{-}9+2.2409e6P_1+7.1332e\text{-}8(P_1)^2$	2	8
2	$-2.4144e\text{-}11+0.4274e6P_2\text{-}1.1182e\text{-}8(P_2)^2$	9.68	38.73
3	$-3.6365e\text{-}11+1.9178e6P_3\text{-}4.5984e\text{-}8(P_3)^2$	5	8
4	$6.346e\text{-}12+0.43275e6P_4+1.9212e\text{-}7(P_4)^2$	55.59	222.35
5	$-2.5302e\text{-}11+1.90844e6P_5+1.8497e\text{-}8(P_5)^2$	15	60
6	$-4.7539e\text{-}12+0.42778e6P_6\text{-}1.0608e\text{-}7(P_6)^2$	54.88	219.5
7	$1.587e\text{-}10+2.6343e6P_7+1.3227e\text{-}8(P_7)^2$	1.25	5

Table 6. Optimization Results of the Real System Sulselbar 150 kV Thermal Power Plant for Two Objective Functions Test

Objective Function	Optimal Value
Active power transmission losses	16.583 MW
Fuel cost	363.176 million (IDR/hour)

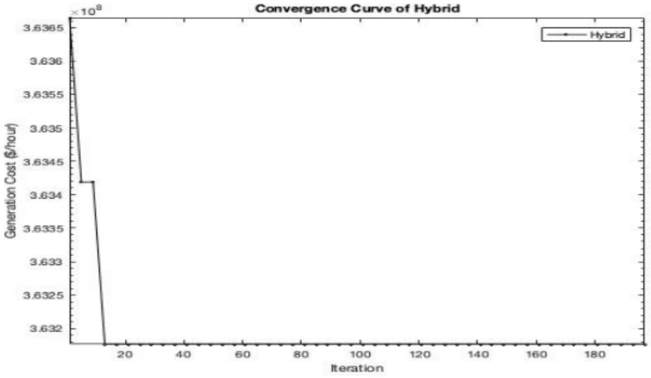

Figure 4. Convergence Curve of Sulselbar Thermal Power Plant Real System

5.3.Case 3: Thermal-Wind Power Plants Integration System

To test the effectiveness of the FOA-ABC hybrid optimization method, the test is carried out on the thermal-wind integration for 6 unit generators and one of wind farm with 165 MW capacity. The test data of the 26 bus IEEE thermal system with 6 unit generators taken from [5] and for a wind power plant is taken from [29]. The wind power parameters are wind speed of 12.5 m/s, cut out speed of 20 m/s, cut in speed of 4 m/s, scale factor (c) of 10, shape factor (k) of 2, direct cost (d) of 7 $/MW, penalty cost ($k_p$) of 6 $/MW, reserve cost ($k_r$) of 10 $/MW. Next, the test is done on two test stages, for the 1st stage, it is carried out on the 26 bus IEEE thermal system without wind integration and for the 2nd stage, it is carried out on the thermal-wind integration system. While the total load demand is 1263 MW.

The simulation results of the FOA-ABC hybrid method for the 1st test can be seen in Table 7, the convergence curve in Figure 5, and the computational time of 241.920238 seconds. As for the simulation results of the FOA-ABC hybrid method for the 2nd test can be seen in Table 8, the convergence curve in Figure 6, and the computational time of 1943.283039 seconds.

Table 7. Optimization Results of the 26 Bus IEEE System Test

Parameters	Optimal Value
P_{G1}	448.0418 MW
P_{G2}	172.0734 MW
P_{G3}	264.3323 MW
P_{G4}	126.0513 MW
P_{G5}	172.7050 MW
P_{G6}	85.1069 MW
TG	1268.3106 MW
P_{LOSSES}	5.3106 MW
FC	14294.0127 $/hour

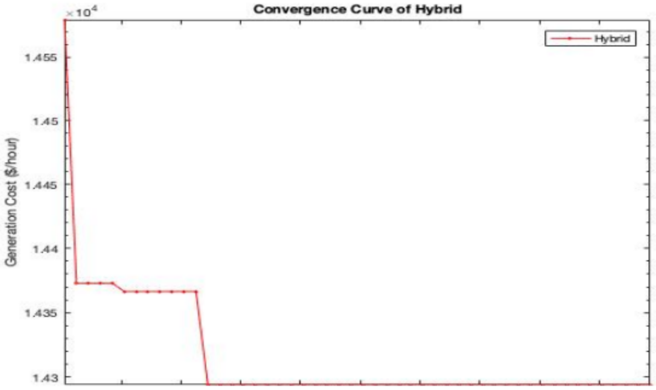

Figure 5. Convergence Curve of Total Fuel Cost of The 26 Bus IEEE System

Table 8. Optimization Results of the Thermal-Wind Integration of the 26 bus IEEE System Test

Parameters	Optimal Value
P_{G1}	428.7003 MW
P_{G2}	157.8251 MW
P_{G3}	249.3052 MW
P_{G4}	111.0073 MW
P_{G5}	155.8120 MW
P_{G6}	67.0806 MW
W	98.57 MW
TG	1273.6010 MW
P_{LOSSES}	5.3005 MW
FC	13088.1208 $/hour
WC	689.9900 $/hour
PC	164.3255 $/hour
RC	215.0226 $/hour
TC	14157.4589 $/hour

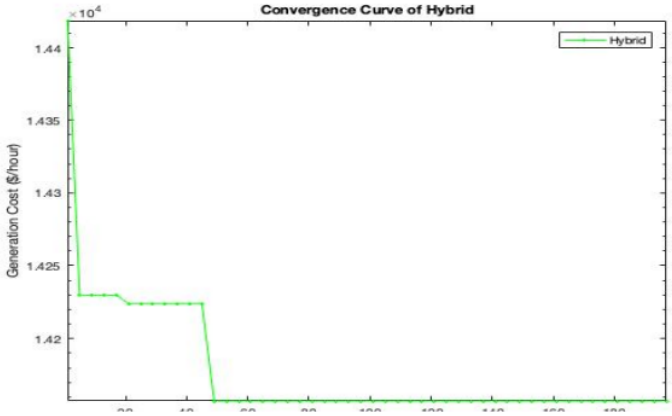

Figure 6. Convergence Curve of Total Fuel Cost of The 26 Bus IEEE Thermal-Wind Integration System

6. COMPARISON OF RESULTS

The FOA-ABC hybrid optimization method is compared with the existing method for the three tested cases to see the extent of the effectiveness of this method for solving the DED problem. For case 1, the test is done at the 30 bus IEEE thermal system, and the simulation results of the FOA-ABC hybrid optimization method for the 1st stage and the 2nd stage can be shown in Table 9 and Table 10. For case 2, the test is carried out on the Sulselbar thermal power plant real system, and simulation results of the FOA-ABC hybrid optimization method can be seen in Table 11. Whereas for case 3, the test is carried out on the 26 bus IEEE system without and wind integration, and the simulation results of the FOA-ABC hybrid optimization method can be seen in Table 12.

For all units in Table 12, it was described as follows: the total cost (TC) in $/hour, reserve cost (RC) in $/hour, penalty cost (PC) in $/hour, direct cost (WC) in $/hour, the total fuel cost of thermal units (FC) in $/hour, power losses (L) in MW, total of generating power (TG) in MW, generated wind power (W) in MW and the thermal units generation power (P_{Gi}) in MW.

Table 9. Comparison of Optimization Results for the 1st Stage Test of the 30 Bus IEEE System

Objective Function	Method	
	Hybrid	FOA
Active power transmission losses	6.912 MW	7.348 MW
Reactive power transmission losses	-8.772 Mvar	-4.989 Mvar
Emission index	0.0585 ton/hour	0.0596 ton/hour

Table 9 shows that comparison of the optimization results of the 30 bus IEEE system for the 1st stage of the FOA-ABC hybrid optimization method for the three tested objective functions are reactive power transmission losses of -8,772 Mvar, active power transmission losses of 6,912 MW and emissions index of 0.0585 ton/hour, the value is smaller than the compared method (FOA), namely 7,348 MW for active power transmission losses, -4,989 Mvar for reactive power transmission losses and 0.0596 ton/hour for emission index. So the difference of active power transmission losses are 0.941 MW or decrease around 5.93 percent. The difference of reactive power transmission losses is -3.783 Mvar or decrease around 24.17 percent. Meanwhile, the difference of emission index is 0.0011 ton/hour or decrease around 1.85 percent.

Table 10. Comparison of Optimization Results for the 2nd Stage Test of the 30 Bus IEEE System

Objective Function	Method		
	Hybrid	FOA	PSO [39]
Fuel Cost	793.688 $/hour	795.327 $/hour	799.986 $/hour
Active power transmission losses	6.754 MW	7.366 MW	9.071 MW
Reactive power transmission losses	-8.985 Mvar	-4.934 Mvar	1.370 Mvar
Emission index	0.069 ton/hour	0.068 ton/hour	0.431 ton/hour
Reactive power reserve margin	0.211	0.211	0.319

Table 10 shows that comparison of the FOA-ABC hybrid optimization method results has a smaller value than FOA and PSO methods of three objective functions for five tested objective functions, namely fuel cost is 793.688 $/hour, reactive power transmission losses is -8.985 Mvar, and active power transmission losses is 6.754 MW. Meanwhile, the value of fuel cost for FOA method is 795.327 $/hour and 799.986 $/hour for PSO method. For active power transmission losses is 6.754 MW for hybrid method, 7.366 MW for FOA Method, and 9.071 for PSO method. While the reactive power transmission losses is 8.985 Mvar for hybrid method, - 4.934 Mvar for the FOA method, and 1.370 Mvar for PSO method. The difference of fuel cost is 1.639 $/hour for the FOA method or decreases around 0.21 percent, and 6.298 $/hour or decreases around 0.79 percent for the PSO method. The difference of active power transmission losses are 0.612 MW or decrease around 8.31 percent for the FOA method, and 2.317 MW or decrease around 25.54 percent for the PSO method. Meanwhile, the difference of reactive power transmission losses are 4.051 Mvar or decrease around 17.89 percent for the FOA method, and 10.355 Mvar or decrease around 86.77 percent for the PSO method.

Table 11. Comparison of Optimization Results for the Sulselbar Power Plant Real System

Objective Function	Method			
	Hybrid	FOA	ABC [40]	Lagrange [41]
Active power transmission losses	16.583 MW	20.303 MW	23.269 MW	23.471 MW
Fuel cost	363.176 million (IDR/hour)	364.787 million (IDR/hour)	366.071 million (IDR/hour)	366.158 million (IDR/hour)

Table 11 shows that the comparison of the FOA-ABC hybrid optimization method results for the Sulselbar power plant real system has a smaller value than FOA, ABC and Lagrange Methods for two tested objective functions, namely fuel cost and losses of active power transmission. The difference of active power transmission losses is 3.72 MW or decrease around 18.32 percent for the FOA method, 6.686 MW or decrease

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around 28.73 percent for the ABC method, and 6.888 MW or decrease around 29.35 percent for the Lagrange method. While the fuel cost is 1.611 million (IDR/hour) or decrease around 0.44 percent for the FOA method, 2.895 million (IDR/hour) or decrease around 0.79 percent for ABC method, and 2.982 million (IDR/hour) or decrease around 0.81 percent for the Lagrange method.

Table 12. Comparison of Optimization Results for Thermal-Wind Integration of the 26 Bus IEEE System

Unit	Without Wind				Wind	
	GA [42]	PSO [42]	PGSA [29]	Hybrid	PGSA [29]	Hybrid
P_{G1}	474.81	447.49	441.01	448.04	399.42	428.70
P_{G2}	178.63	173.32	168.72	172.07	171.47	157.83
P_{G3}	262.21	263.47	262.76	264.33	201.60	249.31
P_{G4}	134.28	139.06	148.47	126.05	109.68	111.01
P_{G5}	151.90	165.48	177.39	172.70	207.98	155.81
P_{G6}	74.18	87.13	77.29	85.11	86.30	67.08
W	-	-	-	-	98.57	98.57
TG	1276.03	1276.01	1275.67	1268.31	1275.03	1273.60
L	13.02	12.96	12.69	5.31	12.00	5.30
FC	15459.00	15450.00	15449.54	14294.01	14192.25	13088.12
WC	-	-	-	-	689.96	689.99
PC	-	-	-	-	39.25	164.33
RC	-	-	-	-	384.34	215.02
TC	15459.00	15450.00	15449.54	14294.01	15305.80	14157.46

Table 12 shows that the comparison of the FOA-ABC hybrid optimization method results has a smaller value than GA, PSO, and PGSA methods for two tested systems, namely of the 26 bus IEEE system for GA, PSO and PGSA methods, and thermal-wind integration system of the 26 bus IEEE for the PGSA method.

For test of the 26 bus IEEE system, the value of a fuel cost for the hybrid method is 14294.01 $/hour. Meanwhile, the fuel cost of the GA method is 15459 $/hour, 15450 $/hour for the PSO method and 15459.54 $/hour for the PGSA method. The difference of fuel cost is 1164.99 $/hour or decrease around 7.54 percent for the GA method, 1155.99 $/hour or decrease around 7.48 percent for the PSO method, and 1165.53 $/hour or decrease around 7.53 percent for the PGSA method. Power losses of the hybrid method is 5.31 MW, while the GA method is 13.02 MW, 12.96 MW for the PSO method, and 12.69 MW for the PGSA method. The difference of power losses is 7.71 MW or decrease around 59.22 percent for the GA method, 7.65 MW or decrease around 59.03 percent for the PSO method, and 7.38 MW or decrease around 58.16 percent for the PGSA method.

For thermal-wind integration testing of the 26 bus IEEE system, the value of a fuel cost for the hybrid method is 13088.12 $/hour. While the PGSA method is 14192.25 $/hour. The difference of fuel cost is 1104.13 $/hour or decrease around 7.78 percent. When the generated wind power is the same for the hybrid and the PGSA methods will be got the wind cost or direct cost of hybrid method is 689.99 $/hour, and 689.96 $/hour for PGSA method. The penalty cost of hybrid method is 164.33 $/hour, and 39.25 $/hour for PGSA method. While reserve cost of hybrid method is 215.02 $/hour, and 384.34 $/hour for PGSA method. Total operation cost of hybrid method is 14157.46 $/hour and 15305.80 $/hour for PGSA method. So, the difference of total operation cost is 1148.34

$/hour or decrease around 7.5 percent. Power losses of thermal-wind integration for the hybrid method is 5.3 MW, and 12.0 MW for the PGSA method. The difference of power losses is 6.7 MW or decrease around 55.83 percent.

7. CONCLUSIONS

To get the best solution of DED problems with multiobjective functions, namely fuel cost, reactive and active power transmission losses, emission index, and reactive power reserve margin, the FOA-ABC hybrid optimization method is proposed. Next, to see the effectiveness of the FOA-ABC hybrid optimization method, the test was carried out in the three different cases, namely, the 30 bus IEEE system that was carried out in two test stages, the Sulselbar thermal power plant real system in Indonesia, and the 26 bus IEEE system without wind integration and wind integration.

The results of conducted tests on the three tested cases showed that the FOA-ABC hybrid optimization method was able to provide the best solution that has been shown by all the obtained values smaller than the obtained values of the compared method. Likewise, the required computational time of the FOA-ABC hybrid optimization method is also fast enough to get the best solution to the complicated DED problem. For future research, we suggest using multiobjective functions that are more complex and difficult in cases that are tested by using new optimization methods.

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