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ADVANCE OPTIMIZATION OF ECONOMIC EMISSION DISPATCH BY PARTICLE SWARM OPTIMIZATION (PSO) USING CUBIC CRITERION FUNCTIONS AND VARIOUS PRICE PENALTY FACTORS

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Abstract

The classical economic dispatch problem could be solved based on single objective function of power system operation by minimizing the fuel cost. However, the single objective function is not sustainable because the environmental issues arise from the emissions generated by fossil-fueled thermal electric power plants. Various pollutants such as sulfur dioxide (SO2), nitrogen oxides (NOX) and carbon dioxide (CO2) affect environmental issues. The economy-environment dispatch problem has been generally solved by considering each objective separately or by applying Weighted Sum Method on both objectives. This paper formulates the solution of dispatch PSO method that considers the impact of various pollutants and various factors such as the price penalty Min-Max, Max-Max, and Average in solving multi-objective problems using cubic criterion function for the cost of fuel and emission values. Multi-objective functions method proposed in this research was validated using IEEE 30-bus systems with six generating units. The results of simulation using Min-Max penalty factor indicated less total fuel cost value compared to the simulation using Max-Max and Average penalty factor. In general, the comparison of Min-Max type= 100%, Max-Max type= 266.9%, and Average type= 191.8%; Max-Max penalty factor provided less emission value with comparison to Min-Max and Average penalty factors. In general, the comparison Max-Max type= 100%, Min-Max type= 102%, and Average type= 100.2% to ETSO while for ETNO and ETCO is not significantly different; Average penalty factor provided less fuel cost value compared to Max-Max and Average penalty factor. In general, the comparison of Average type= 100%, Min-Max type= 101.8%, and Max-Max type= 100.3%.

Keywords: Economic-Emission Dispatch, Multi-Objective, Cubic Criterion Function, Price Penalty Factors, Particle Swarm Optimization.

INTRODUCTION

The electrical energy supply system faces its main problems, namely generator efficiency, transmission efficiency, distribution system, or combination of these three problems. Previous efforts to solve these problems were concentrated on minimizing operational cost of fuel consumption which has become the objective function and other requirements as the constraints. There were various OPF formulation depended on its objective functions and certain constraints being developed. Previous researches were concentrated on OPF problems solving by considering the system security [1], [2].

Recent optimizations techniques have been developed in a different area of electrical energy system were single objective function PSO, multiple objective functions PSO, and hybrid PSO. Singh and Erlich had attempted to estimate based on optimal block incremental cost obtained from the instantaneous incremental heat rate curve of generating unit using PSO approach [3]. K. Thanushkodi has achieved a satisfying result in applying PSO technique to solve Economic Dispatch using a smooth and non-smooth cost functions by considering the effects of valve-point loading [4],[5].

Z.Al-Hamouz has successfully demonstrated PSO algorithm application to solve Optimal Reactive Power Planning problems by reducing short-term operating costs and investment costs [6].

Another problem on electricity today was caused by pollutants resulted by fuel consumption process. Energy source diversification had been done. One of its implementation was the usage of coal as power plant fuel which was effective in reducing energy costs. However, the use of coal as fuel resulted carbon dioxide (CO_2), sulfur dioxide (SO_2) and oxides of nitrogen (NO_X) which polluted air. These pollutants caused acid rain which contributed on forest and plantation damages. These pollutants ignited greenhouse effect which increased global temperature and caused other side effects.

To anticipate the pollutant problem, the PSO proposed algorithm containing multi-objective functions, i.e. economic objective function (fuel cost and transmission losses) and emission objective function.

ECONOMIC - EMISSION PROBLEM FORMULATION.

OPF problem is non-linear optimization problem with objective function and non-linear constraints. It was used to calculate the generation system and distribution of electric power in order to obtain the best and most profitable results. Methods of problem solving in the conventional OPF, namely the Newton method, Gradient and Interior Point, had been used extensively. OPF problem solving required non-linear equations, the description of optimization, security and operation of power systems. According to the designation, the optimization problem can be mathematically expressed by Equation (1) to Equation (3).

$$\text{Minimize} \quad F(x,u) \tag{1}$$

$$\text{Subject to} \quad g(x,u) = 0 \tag{2}$$

$$h(x,u) \le 0 \tag{3}$$

where,

$$x^T = \left[\delta \;\; V_L^T \right]$$

$$u^T = \left[P_G^T \;\; V_G^T \;\; t^T \;\; Q_{SH}^T \right]$$

Equation (1) defines the general objective function, while equality constraints represented in Equations (2) and (3) were the inequality constraints of vector arguments x and u. x is the state variables and u is the vector of control variables. The state variables are angle (δ) and voltage (V_L) of load buses. The control variables are generator active power (P_G), bus voltage (V_G), transformers tap-setting (t), and shunt capacitors/reactors (Q_{SH}).

Objective Function

The economic-emission dispatch for all-thermal power generation systems was for-mulated as a multi-objective optimization problem. As a result, the economic-emission dispatch problem considers four conflicting and non-commensurable objec-tives. Besides the fuel cost, these objec-tives were sulphur-dioxide emission SO_2, nitrogenoxide emission NO_X and carbon-dioxide CO_2 emissions. Mathematically, these objective functions are expressed as follows :

Economic Objective Function

Operating thermal plants total costs includes labor and maintenance costs in addition to the costs of fuel and other supplies. In general, the economic dispatch process considers the cost of the fuel burnt in the fossil units. Rather than being neglected, the other costs are commonly assumed as fixed percentage of the incoming fuel costs. The input to the thermal plant is generally measured in MBtu/h known as "heat-rate" curve and the output power is in MW. The heat-rate curve is converted to the fuel cost curve representing the relationship of the operating cost of a fossil-fired thermal unit and its output power. This cost is approximated as a cubic function model of the real power generation.

The first objective F_TBB is the fuel cost function of the thermal generating units as expressed in Equations (4)

$$F_T BB = \sum_{i=1}^{NG} F_i\,(P_{Gi})$$

$$= \sum_{i=1}^{NG} (a_1 P_{Gi}^3 + b_1 P_{Gi}^2 + c_1 P_{Gi} + d_1) \quad \$/hr \quad (4)$$

where, P_{Gi} is the real power output of an *i*th generator; NG is the number of thermal generating units; a_i, b_i , c_i and d_i, are the fuel cost curve coefficients of an *i*th generator, respectively.

Emission Objective Function

The objective for minimization of emission quantity minimization is formulated by including the reduction of emission as an objective by following equation :

The second objective is total sulphur dioxide emission (E_TSO) referring to the amount of SO_2 emission modeled as a cubic function of the output power of the generating units which is expressed in Equation (5) :

$$E_T SO = \sum_{i=1}^{NG} (\mathrm{a}_{SOi} P_{Gi}^3 + \mathrm{b}_{SOi} P_{Gi}^2 + \mathrm{c}_{SOi} P_{Gi} + \mathrm{d}_{SOi}) \quad kg/hr \quad (5)$$

$\mathrm{a}_{SOi}, \mathrm{b}_{SOi}, \mathrm{c}_{SOi}, \mathrm{d}_{SOi}$ are sulphur-dioxide emiss-ion coefficients of generator unit *i*

The third objective is total nitrogen oxide (E_TNO) emission referring to the amount of NO_X emission as expressed in Equation (6):

$$E_T NO = \sum_{i=1}^{NG} (\mathrm{a}_{NOi} P_{Gi}^3 + \mathrm{b}_{NOi} P_{Gi}^2 + \mathrm{c}_{NOi} P_{Gi} + \mathrm{d}_{NOi}) \quad kg/hr \quad (6)$$

$\mathrm{a}_{NOi}, \mathrm{b}_{NOi}, \mathrm{c}_{NOi}, \mathrm{d}_{NOi}$ are nitrogen-oxide emiss-ion coefficients of generator unit *i*

The fourth objective is total carbon dioxide emission (E_TCO) referring to the amount of CO_2 emission as expressed in Equation (7):

$$E_T CO = \sum_{i=1}^{NG} (\mathrm{a}_{COi} P_{Gi}^3 + \mathrm{b}_{COi} P_{Gi}^2 + \mathrm{c}_{COi} P_{Gi} + \mathrm{d}_{COi}) \quad kg/hr \quad (7)$$

$\mathrm{a}_{COi}, \mathrm{b}_{COi}, \mathrm{c}_{COi}, \mathrm{d}_{COi}$ are carbon-dioxide emiss-ion coefficients of generator unit *i*

These objective functions are subject to various equality and inequality constraints as seen in Equation (8).

$$\sum_{i=1}^{NG} P_{Gi} = P_D + P_L \quad (8)$$

where P_D is the total load demand and P_L is the transmission power losses as a function of the real power generation.

Generation capacity limits can be seen in Equation (9).

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad (9)$$

where $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the minimum and maximum generation limit of the i^{th} generating unit.

Formulation of Multi-Objective Function

Fuel cost and emission are the two objectives to be minimized simultaneously in a bi-objective problem. Three types of price penalty factors are applied to convert this multi-objective optimization to a single objective optimization problem for the various emissions. The next problem is related to the impact of all three emissions is solved for all emissions simultaneously at the same power demand.

Bi-Objective Optimization of Cost and Emission.

Three problems are separately formulated for every emission, as expressed by Equations (10), (11), and (12).

$$F_T SO = \sum_{i=1}^{NG} \begin{bmatrix} (a_i P_{Gi}^3 + b_i P_{Gi}^2 + c_i P_{Gi} + d_i) + \\ h_{SOi} (a_{SOi} P_{Gi}^3 + b_{SOi} P_{Gi}^2 + c_{SOi} P_{Gi} + d_{SOi}) \end{bmatrix}$$

$$\$/hr \qquad (10)$$

$$F_T NO = \sum_{i=1}^{NG} \begin{bmatrix} (a_i P_{Gi}^3 + b_i P_{Gi}^2 + c_i P_{Gi} + d_i) + \\ h_{NOi} (a_{NOi} P_{Gi}^3 + b_{NOi} P_{Gi}^2 + c_{NOi} P_{Gi} + d_{NOi}) \end{bmatrix}$$

$$\$/hr \qquad (11)$$

$$F_T CO = \sum_{i=1}^{NG} \begin{bmatrix} (a_i P_{Gi}^3 + b_i P_{Gi}^2 + c_i P_{Gi} + d_i) + \\ h_{COi} (a_{COi} P_{Gi}^3 + b_{COi} P_{Gi}^2 + c_{COi} P_{Gi} + d_{COi}) \end{bmatrix}$$

$$\$/hr \qquad (12)$$

Optimization of Four Objectives.

Total fuel cost for SO_2, NO_X, and CO_2 emissions is given by Equation (12).

$$F_{TOTAL} = \sum_{i=1}^{NG} \begin{bmatrix} (a_i P_{Gi}^3 + b_i P_{Gi}^2 + c_i P_{Gi} + d_i) + \\ h_{SOi} (a_{SOi} P_{Gi}^3 + b_{SOi} P_{Gi}^2 + c_{SOi} P_{Gi} + d_{SOi}) + \\ h_{NOi} (a_{NOi} P_{Gi}^3 + b_{NOi} P_{Gi}^2 + c_{NOi} P_{Gi} + d_{NOi}) + \\ h_{COi} (a_{COi} P_{Gi}^3 + b_{COi} P_{Gi}^2 + c_{COi} P_{Gi} + d_{COi}) \end{bmatrix}$$

$$\$/hr \qquad (12)$$

Formulation of Price Penalty Factors

The price penalty factor for the combined economic-emission dispatch problem is the ratio of fuel cost to emission value. The role of all penalty factors is to transfer the physical meaning of emission criterion from weight of the emission to the fuel cost for emission.

The use of three types of price penalty factor in problem solving optimization PSO method developed in this study provides an alternative option optimization results OPF problem, whether focused on the cost of fuel or emissions produced as a main objectives function. The price penalty factor Min-Max is expressed in Equation (13), (14), and (15). The price penalty Factor Max-Max can be seen in Equation (16), (17), and (18). Meanwhile the average is shown in Equation (19), (20), and (21).

Price Penalty Factor Min-Max

$$h_{MinSOi} = \frac{(a_i P_{Gimin}^3 + b_i P_{Gimin}^2 + c_i P_{Gimin} + d_i)}{(a_{SOi} P_{Gimax}^3 + b_{SOi} P_{Gimax}^2 + c_{SOi} P_{Gimax} + d_{SOi})} \qquad (13)$$

$$h_{MinNOi} = \frac{(a_i P_{Gimin}^3 + b_i P_{Gimin}^2 + c_i P_{Gimin} + d_i)}{(a_{NOi} P_{Gimax}^3 + b_{NOi} P_{Gimax}^2 + c_{NOi} P_{Gimax} + d_{NOi})} \qquad (14)$$

$$h_{MinCOi} = \frac{(a_i P_{Gimin}^3 + b_i P_{Gimin}^2 + c_i P_{Gimin} + d_i)}{(a_{COi} P_{Gimax}^3 + b_{COi} P_{Gimax}^2 + c_{COi} P_{Gimax} + d_{COi})} \qquad (15)$$

Where

h_{MinSOi} - Min-Max of SO_2 Emission

h_{MinNOi} - Min-Max of NO_X Emission

h_{MinCOi} - Min-Max of CO_2 Emission

Price Penalty Factor Max-Max

$$h_{\mathrm{MaxSOi}} = \frac{(a_i P^3_{\mathrm{Gimax}} + b_i P^2_{\mathrm{Gimax}} + c_i P_{\mathrm{Gimax}} + d_i)}{(a_{\mathrm{SOi}} P^3_{\mathrm{Gimax}} + b_{\mathrm{SOi}} P^2_{\mathrm{Gimax}} + c_{\mathrm{SOi}} P_{\mathrm{Gimax}} + d_{\mathrm{SOi}})} \quad (16)$$

$$h_{\mathrm{MaxNOi}} = \frac{(a_i P^3_{\mathrm{Gimax}} + b_i P^2_{\mathrm{Gimax}} + c_i P_{\mathrm{Gimax}} + d_i)}{(a_{\mathrm{NOi}} P^3_{\mathrm{Gimax}} + b_{\mathrm{NOi}} P^2_{\mathrm{Gimax}} + c_{\mathrm{NOi}} P_{\mathrm{Gimax}} + d_{\mathrm{NOi}})} \quad (17)$$

$$h_{\mathrm{MaxCOi}} = \frac{(a_i P^3_{\mathrm{Gimax}} + b_i P^2_{\mathrm{Gimax}} + c_i P_{\mathrm{Gimax}} + d_i)}{(a_{\mathrm{COi}} P^3_{\mathrm{Gimax}} + b_{\mathrm{COi}} P^2_{\mathrm{Gimax}} + c_{\mathrm{COi}} P_{\mathrm{Gimax}} + d_{\mathrm{COi}})} \quad (18)$$

Where

h_{MaxSOi} - Max-Max of SO_2 Emission
h_{MaxNOi} - Max-Max of NO_X Emission
h_{MaxCOi} - Max-Max of CO_2 Emission

Price Penalty Factor Average

$$h_{\mathrm{AveSOi}} = \frac{\left(F_T BB_{SO} P_{\mathrm{Gimin}} / E_T SOP_{\mathrm{Gimax}}\right) + \left(F_T BB_{SO} P_{\mathrm{Gimax}} / E_T SOP_{\mathrm{Gimax}}\right)}{2} \quad (19)$$

$$h_{\mathrm{AveNOi}} = \frac{\left(F_T BB_{NO} P_{\mathrm{Gimin}} / E_T NOP_{\mathrm{Gimax}}\right) + \left(F_T BB_{NO} P_{\mathrm{Gimax}} / E_T NOP_{\mathrm{Gimax}}\right)}{2} \quad (20)$$

$$h_{\mathrm{AveCOi}} = \frac{\left(F_T BB_{CO} P_{\mathrm{Gimin}} / E_T COP_{\mathrm{Gimax}}\right) + \left(F_T BB_{CO} P_{\mathrm{Gimax}} / E_T COP_{\mathrm{Gimax}}\right)}{2} \quad (21)$$

Where

h_{AveSOi} - Average of SO_2 Emission
h_{AveNOi} - Average of NO_X Emission
h_{AveCOi} - Average of CO_2 Emission

PARTICLE SWARM OPTIMIZATION ALGORITHM

PSO algorithm is based on particles inside a population that work together to solve the existing problems regardless of its physical positions. PSO algorithm combines local search method and global search method to balance exploration and exploitation. PSO has several similarities with GA. The system is started by a population formed by random solutions, and system will seek for optimization through random generation changes [7],[8].

Each particle stores the position traces in the search space is defined as the best solution has been achieved. Personal best (pbest) is the best the value of the particle, while the global best (gbest) is the best value which takes into account all the particles in the population. Each particle in every iteration is given information about the latest gbest value that becomes information sharing mechanism in one direction to make the process of finding the best solution with rapid convergence movement.

PSO algorithm consists of three steps, namely determining the particle's position and velocity, updating velocity, and updating position. The position x^i_k and velocity v^i_k of particles are randomly initialized using the value of the highest and lowest variable according to the design, while the rand (r) is a random value between 0 and 1. Each particle tries to update its position using such information, current position, current velocity, distance between the current position of the pbest and the current position of gbest. Mathematically, particle velocity update (v^i_{k+1}) is expressed by Equation (22).

$$v^i_{k+1} = v^i_k + c_1 r_1 (p^i_k - x^i_k) + c_2 r_2 (p^g_k - x^i_k) \quad (22)$$

Achieving the results obtained from the new velocity calculation for each particle based on the distance from pbest owned and distance from the gbest position. Particle position

update (x^i_{k+1}) is formulated on Equation (23).

$$x^i_{k+1} = x^i_k + v^i_{k+1} \quad (23)$$

Table 1. Active power limit of each plant

Generator Bus	Pmin (MW)	Pmax (MW)
P_1	50,00	200,00
P_2	20,00	80,00
P_5	15,00	50,00
P_8	10,00	50,00
P_{11}	10,00	50,00
P_{13}	12,00	40,00

SIMULATION RESULTS OF MULTI-OBJECTIVE DISPATCH PROBLEM

Optimization studies using the IEEE-30 Bus Test System has 6 units of thermal power plant at bus 1 (P_1), bus 2 (P_2), bus 5 (P_5), bus 11 (P_{11}), and bus 13 (P_{13}). Optimization problem is formulated in four conflicting objective functions, namely fuel costs objective function (F_TBB) as Equation (4), SO_2 emission objective function (E_TSO) as Equation (5), NO_X emission (E_TNO) objective function as Equation (6), and CO_2 emission objective function (E_TCO) as Equation (7).

Each generator has a generator limits, fuel cost coefficients, SO_2 emission coefficients, NO_X emission coefficients, and CO_2 emission coefficients in the form of a cubic equation. Types of price penalty factors used by a generator are Min-Max, Max-Max, and Average.

Table 1. shows the active power limit of each plant. The coefficient of fuel cost and emission coefficients of each plant are shown in Table 2.

Table 2. The coefficient of fuel cost and emission coefficients of each plant

Objective	**Coefficients**	**Generator Bus**					
		P_1	**P_2**	**P_5**	**P_8**	**P_{11}**	**P_{13}**
Fuel Cost **\$/hr**	a_i	0,0010	0,0004	0,0006	0,0002	0,0013	0,0004
	b_i	0,0920	0,0250	0.0750	0,1000	0,1200	0,0840
	c_i	14,50	22,00	23,00	13,50	11,50	12,50
	d_i	-136,00	-3,50	-81,00	-14,50	-9,75	75,60
Emission SO_2 **kg/hr**	a_{SOi}	0,0005	0,0014	0,0010	0,0020	0,0013	0,0021
	b_{SOi}	0,150	0,055	0,035	0,070	0,120	0,080
	c_{SOi}	17,00	12,00	10,00	23,50	21,50	22,50
	d_{SOi}	-90,00	-30,50	-80,00	-34,50	-19,75	25,60
Emission NO_2 **kg/hr**	a_{NOi}	0,00 12	0,0004	0,0016	0,0012	0,0003	0,0014
	b_{NOi}	0,0520	0,0450	0,0500	0,0700	0,0400	0,0240
	c_{NOi}	18,50	12,00	13,00	17,50	8,50	15,50
	d_{NOi}	-26,00	-35,00	-15,00	-74,00	-89,00	-75,00
Emission CO_2 **kg/hr**	a_{COi}	0,0015	0,0014	0,0016	0,0012	0,0023	0,0014
	b_{COi}	0,0920	0,0250	0,0550	0,0100	0,0400	0,0800
	c_{COi}	14,0	12,5	13,5	13,5	21,0	22,0
	d_{COi}	-16,0	-93,5	-85,0	-24,5	-59,0	-70,0

Table 3. optimization of the total fuel costs

Output Generator	**Power Demand 250 MW**			**Power Demand 300 MW**		
	Min-Max	***Max-Max***	***Average***	***Min-Max***	***Max-Max***	***Average***
P_1 MW	57,6244	50,0000	50,0124	70,8686	58,3956	52,1467
P_2 MW	41,0046	45,4282	48,6034	59,9754	65,7594	74,2059
P_5 MW	20,9845	26,3671	23,3791	35,9990	42,5597	40,3564
P_8 MW	50,0000	50,0000	50,0000	50,0000	50,0000	50,0000
P_{11} MW	49,0339	42,3893	42,2406	50,0000	50,0000	50,0000
P_{13} MW	35,5944	40,0000	40,0000	40,0000	40,0000	40,0000
Power Losses MW	4,2418	4,1846	4,2356	6,8430	6,7147	6,7091
F_TBB ***\$/hr***	5181,2	5081,1	5079,7	6772,8	6667,5	6649,9
E_TSO ***kg/hr***	6352,7	6143,0	6181,1	7878,4	7665,7	7727,7
E_TNO ***kg/hr***	4452,8	4376,4	4379,6	5771,1	5557,7	5485,7
E_TCO ***kg/hr***	5217,9	5027,2	5041,4	6797,4	6591,4	6605,5
F_{TOTAL} ***\$/hr***	7487,1	19832,0	14547,0	9938,5	26525,0	19067,0

Table 4. The Total Fuel

Cost ***\$/hr***	**Power Demand 225 MW**			**Power Demand 300 MW**		
	Min-Max	***Max-Max***	***Average***	***Min-Max***	***Max-Max***	***Average***
F_TBB	4488,400	4402,100	4395,800	6772,800	6667,500	6649,900
F_TSO	647,177	4399,100	2721,300	1066,700	6845,300	4125,000
F_TNO	674,219	4392,000	2732,100	1079,400	6715,200	4149,200
F_TCO	609,114	3932,300	2733,300	1019,600	6296,600	4143,000
F_{TOTAL}	6418,900	17126,000	12583,000	9938,500	26525,000	19067,000

Objective Functions Optimization ,Total Fuel Cost , Fuel Cost of SO_2 emission, Fuel Cost of NO_X emission, and Fuel Cost of CO_2 emission.

The simulation is done by combining F_TBB, Fuel Cost of SO_2 emission, Fuel Cost of NO_X emission, and Fuel Cost of CO_2 emission simultaneously to obtain the optimal total fuel costs in electric power system taking into account the constraints that have been specified.

Table 3. shows the best results of the optimization of the total fuel costs F_{TOTAL} within three types of price penalty factors for consideration in operating the thermal electric power system.

Table 4. Shows that the total Fuel Cost F_{TOTAL} is determined by the cost of emissions F_TSO, F_TNO, and F_TCO. The emission costs on Min-Max type is far below the value of F_TBB with unsignificant difference, while the emission costs on Max-Max type is almost similar to the value of F_TBB with unsignificant difference.

Figure 1. shows the results of four cost optimization objective functions are obtained from the total Fuel Cost on power demand 225 to 300 MW. F_{TOTAL} is the result of a combination of F_TBB, F_TSO, F_TNO, and F_TCO. Costs of F_TSO, F_TNO, and F_TCO indicates unsignificant differences on any type of price penalty factors in the same power demand.

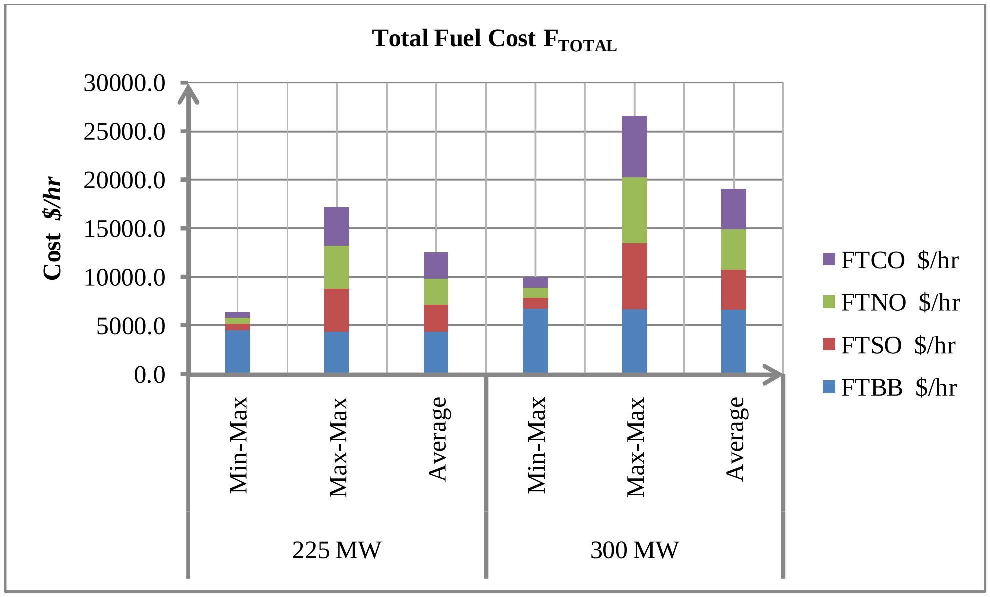

Figure 1. Result of Four Cost Optimization Objective Fucntions

Table 5. The results of optimization FTBB and ETSO for Max-Max type between PSO method and Lagrange's algorithm

Price Penalty Factor	**Power Demand MW**	$F_T\text{BB}$ *\$/hr*		$E_T\text{SO}$ *kg/hr*	
		PSO	**LAG [9]**	**PSO**	**LAG [9]**
Max-Max	**150**	2734,200	2729,349	3193,600	3091,648
	175	3236,300	3475,409	3904,900	4142,176
	200	3784,900	4210,303	4670,600	5053,584
	225	4402,300	5130,534	5426,100	6106,498

Table 6. Results of E_TNO optimization for Max-Max type

Price Penalty Factor	**Power Demand MW**	$E_T\text{NO}$ *kg/hr*		$E_T\text{CO}$ *kg/hr*	
		PSO	**LAG [9]**	**PSO**	**LAG [9]**
Max-Max	150	2424,600	2448,218	2607,100	2537,122
	175	2879,700	2604,886	3178,000	3613,531
	200	3373,200	3102,077	3771,500	4473,369
	225	3877,600	3798,383	4403,000	5502,522

OPTIMIZATION STUDY OF PSO METHOD AND LAGRANGE'S ALGO-RITM (LAG) FOR MULTI-OBJECTIVE FUNCTIONS

Table 5 shows the results of optimization FTBB and ETSO for Max-Max type between PSO method and Lagrange's algorithm on the power demand 150 to 225 MW. FTBB and ETSO of PSO method is always better than the Langrange's algorithm and there are significant differences. Figure 2. suggests that results of optimizaziton F_TBB for Max-Max type, PSO method is better than the Langrange's algorithm on the power demand 175 to 225 MW, while on the power demand 150 MW was not a significant difference. The results of PSO method in the form of a straight line (linear) and the greater power demand yield greater fuel cost.

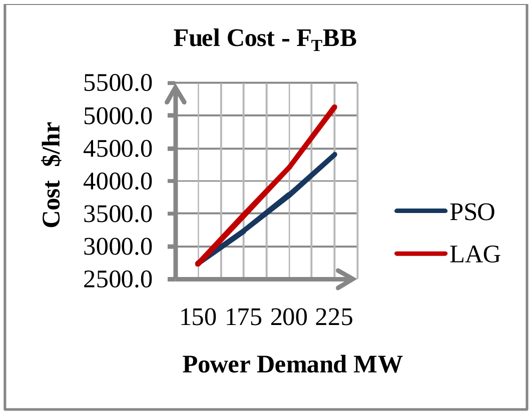

Figure 2. Results of Optimization F_TBB for Max-Max type

Figure 3. shows the results of E_TSO optimization for Max-Max type, PSO method is better than the Langrange's algorithm on the power demand 175 to 225 MW. The largest difference occurs in the results of E_TSO optimization on the power demand 225 MW is 680.398 kg / hr.

As results of E_TNO optimization for Min-Max type, Table 6 shows the results of E_TNO optimization for Max-Max type. Lagrange's algorithm is better than the PSO method, but the results of E_TSO optimization, PSO method is better than Lagrange's algorithm.

Figure 4. shows the results of E_TNO optimization Lagrange's algorithm for Max-Max type has a different shape to results of E_TNO optimization Lagrange's algorithm for Min-max type. E_TNO of PSO method produces the same form for both types.

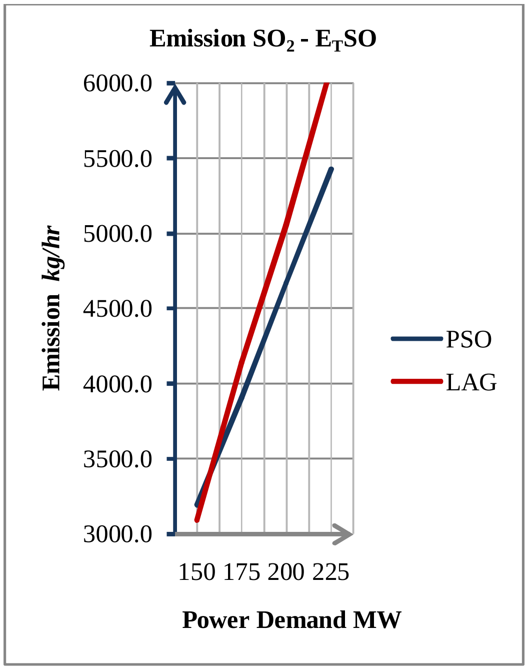

Figure 3. Results of E_TSO optimization for Max-Max type

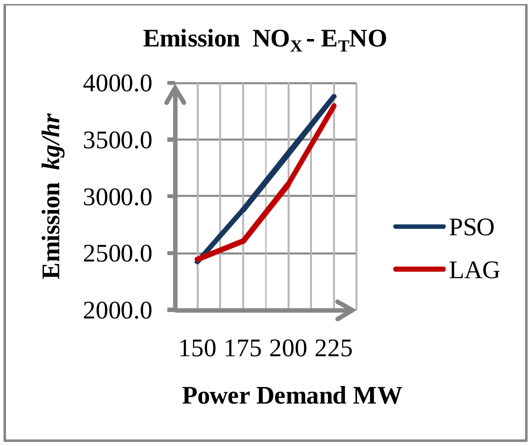

Figure 4. The results of E_TNO optimization Lagrange's algorithm for Max-Max type

Based on the results of E_TNO optimization , PSO method has better consistency, accuracy, and stability in all objective functions compared to Lagrange's algorithm. Figure 5 shows the detailed results of E_TCO optimization between PSO method and Lagrange's algorihtm which suggests that the results of PSO method is always better, especially on the power demand of

175, 200, and 225 MW. The largest difference occurs on the power demand of 225 MW is 1098.522 kg / hr, while the power demand of 175 MW is 435.531 kg / hr

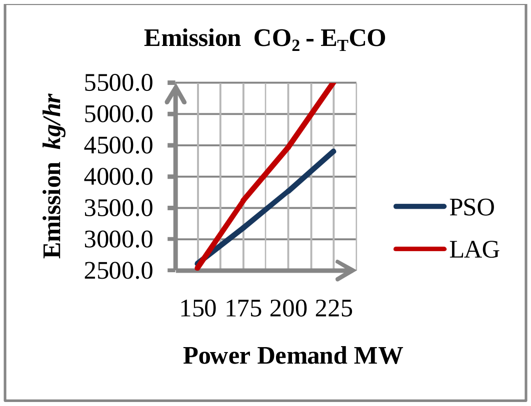

Figure 5. The detailed results of E_TCO optimization between PSO method and Lagrange's algorihtm

Table 7. shows the results of the objective function total fuel cost F_{TOTAL} optimization and network power losses between the PSO method and Lagrange's algorithm for Max-Max type. There are very significant differences between the results of the objective function total fuel cost F_{TOTAL} optimization of PSO method and Lagrange's algorithm, especially on the power demand 175 to 225 MW. The results of the objective function total fuel cost F_{TOTAL} optimization, PSO method is always better on every power demand.

Table 7. Results of the objective function total fuel cost FTOTAL optimization and network power for the Max-Max Price Penalty Factor

Power Demand MW	**F_{TOTAL} $/hr**		**Power Losses MW**
	PSO	**LAG [9]**	
150	10385,000	10264,566	1,7201
175	12425,000	13251,517	2,1799
200	14642,000	16077,409	2,5073
225	17125,000	19661,328	3,4263

Network power losses on each power demand is obtained from PSO method, because the Lagrange's algorithm does not consider or ignore network power losses. Figure 6. shows the different results of the objective function total fuel cost F_{TOTAL} optimization between PSO method and Lagrange's algorithm.

Real difference in the results of optimization occurs on the power demand of 225 MW is $ 2536.328 / hr, while on the power demand of 175 MW is $ 826 / hr.

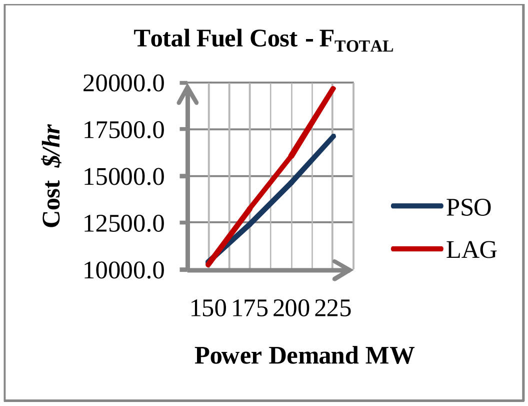

Figure 6. The different results of the objective function total fuel cost FTOTAL optimization between PSO method and Lagrange's algorithm

Figure 7 is a network power losses of PSO method for Max-Max type on the power demand 150 to 225 MW.

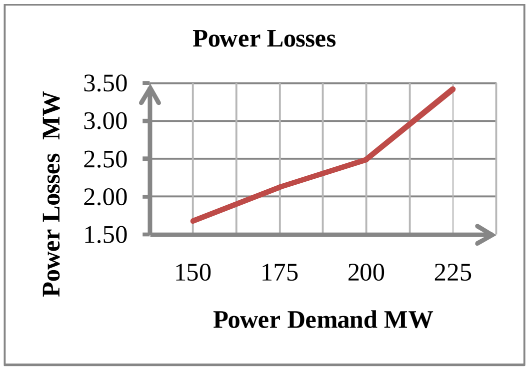

Figure 7. A network power losses of PSO method for Max-Max type on the power demand 150 to 225 MW

There is no significant difference between network power losses for Min-Max and Max-Max type of the shape and percentage. Network power losses is not linear-shaped, but there is a sharp rise on the power demand above 200 MW.

Figure 8 shows the difference voltages at bus 1 to bus 30 on the power demand 150 to 300 MW for Min-Max type. The voltage at the PV buses and slack bus has not changed or equal to the value of the initial voltage on the start, but the PQ bus voltage is changed. Great power demand on the PQ bus will decrease the voltage. However, it should not exceed 0.95 pu. The voltage at bus 26 and bus 30 has a large difference voltage between the power demand 150 and 300 MW, compared to other PQ buses.

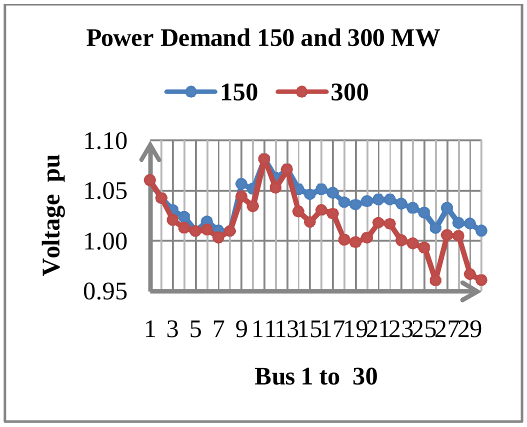

Figure 8. The difference voltages at bus 1 to bus 30 on the power demand 150 to 300 MW for Min-Max type

CONCLUSION

1. The results of PSO method optimization had been proved better than the Lagrange's algorithm. Innovation in form of recent improvement by using the fuel cost function models of cubic form and three price penalty factors namely Min-Max, Max-Max, and Average while considering the network power losses was be able to solve the OPF problem simultaneously.
2. Price penalty factor of Min-Max, Max-Max, Average, and fuel cost function model of the cubic form to solve OPF using PSO method was able to provide an optimization alternative.
   1) The type of Min-Max produced the best at minimum cost of F_TSO, F_TNO, F_TCO, and F_{TOTAL} compared to Max-Max and Average types. In general, the comparison of Min-Max type= 100%, Max-Max type= 266.9%, and Average type = 191.8%.
   2) Average type produced the best F_TBB separately or in combination as compared to Min-Max and Max-Max types. In general, the comparison of Average type= 100%, Min-Max type= 101.8%, and Max-Max type= 100.3%.
   3) Max-Max type produced the lowest E_TSO emissions, E_TNO, and E_TCO separately or in combination compared to Min-Max and average types. In general, the comparison the type of Max-Max = 100%, Min-Max type = 102%, and Average type = 100.2% for E_TSO. Meanwhile, there was no significant difference between ETNO and ETCO.

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