Thunderstorm Algorithm for Assessing Thermal Power Plants of the Integrated Power System Operation with an Environmental Requirement

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***Abstract*—This paper introduces and proposes a new intelligent computation entitled Thunderstorm Algorithm (TA) which is implemented to assess the power system operation presented using the IEEE-62 bus system model with considering an environmental requirement. Simulations showed that TA has ability to search the solution with good performances as given numerical and graphical results. The proposed algorithm of TA seems strongly to be a new promising opportunity for solving an integrated dispatch problem covered in pollutant production and fuel consumption aspects. Results obtained show that TA is executed in the short time and it reaches the optimal solution in the fast convergence while striking points give different implications on the individual performances at overall phases.**

Keyword-Economic dispatch, Emission dispatch, Power system, Thunderstorm algorithm

I. INTRODUCTION

Practically, an integrated power system is managed using many strategies for conveying electric energy from generator sites to load demand areas with considering operational conditions belonged in equality and inequality constraints for searching the optimal scenario of the committed power output to meet a total demand at a certain period time of the operation. Currently, an environmental protection also forces the power system operation to control pollutant productions at thermal power plants related to the fossil fuel combustion for decreasing air contaminants from various gaseous materials, such as, CO; CO2; SOx; and NOx [1]-[5]. Furthermore, the environmental requirement should be included in the power system operation which is represented in a financial compensation as the impact of the pollutant discharge while producing power outputs as given in a certain portion at thermal power plants [5]-[8]. By considering the pollutant problem, the committed power output scenarios become more complex problems and very important cases for deciding suitable shared power productions under operational limitations in order to reach the economic budget and to assess the fuel consumption included material discharges throughout the optimized decision. To treat these conditions, both different targets need to combine mathematically into single objective function which is required by some constraints to obtain the optimal solution in feasible ranges of the operation using numerous methods based on the total cost of fuel consumption and pollutant production problems [8]-[13].

Many previous studies have been proposed and applied to solve this problem with various categories for defining the committed power output of generating units with decreasing the total fuel cost and reducing the pollutant production for the power system operation as the balance between pollutant and economic aspects using classical and evolutionary methods [3], [6], [10], [13]. In detail, conventional approaches cover mathematical programs in several techniques, such as quadratic programming; gradient search; Newton's method; dynamic programming; linear programming; lambda iteration; and Lagrangian relaxation. On the other hand, intelligent computations have been developed for improving performances of classical techniques in various applications. These evolutionary methods use optimization techniques, such as genetic algorithm, neural network, simulated annealing, evolutionary programming, ant colony algorithms, particle swarm optimization, and harvest season artificial bee colony algorithm. Technically, classical approaches safer for environmental protection requirements while the economic assessment considering only a total fuel cost and it cannot meet complex cases under various limitations for the power system condition and the environmental situation [10], [14].

Recently, intelligent computations are frequently applied to various problems based on optimization techniques for mimicking behaviours of entities in nature to replace classical methods in numerous evolutionary algorithms. In these approaches, many previous proposed methods are popular and selected to carry out optimization problems included in the power system operation. The latest intelligent computation is harvest season artificial bee colony algorithm inspired by the harvest season situation of flowers and bee's movements for exploring the area in order to get foods [5], [13], [15]. Its powerful is presented in the smooth convergence speed to select the optimal solution, faster iteration for exploring the population, and better quality on the computational efficiency [14]. Moreover, this paper presents an intelligent computation inspired by a natural phenomenon as a new evolutionary algorithm entitled Thunderstorm Algorithm (TA). As the novel proposed technique, this algorithm is applied to the power system for assessing the economic operation with considering an emission standard as an effort for decreasing pollutant productions at the thermal power plants embedded in the fuel consumption. This paper also presents other performances of TA for searching the optimal solution with its procedures as a new opportunity of a new algorithm.

II. THUNDERSTORM ALGORITHM

For the early idea, Benjamin Franklin was demonstrated to test the theory of lightning erected in Philadelphia while waiting for completion of the spire, he practiced his idea of a flying object using a kite [16]. Furthermore, during the next thunderstorm, he noticed the string stretching out and a spark jumped while the rain fallen during the storm had soaked the line and made it conductive. Recently, its natural behaviours become more attracting topics as previous works with numerous discussions for searching suitable models and understanding the natural phenomenon. As mentioned before, nowadays the lightning is considered as an atmospheric discharge which typically occurs during thunderstorms or other possibility factors such as volcanic eruptions or dust storms. In these cases, the lightning development is produced by several steps in terms of Charge separation for providing the first process in the generation of lightning, Leader formation for the moving thundercloud over the Earth's surface to induce the ground charge follows the movement of the cloud, and Discharge channel when the electric field becomes strong enough for creating a point of the striking between clouds and the ground. By considering the charge as illustrated in Fig. 1, a lightning process is an electric discharge in the form of a spark in a charged cloud that thunder clouds are charged with the negative charge location is deployed in the lower part and the positive charge centre is located at the opposite up [16]-[18].

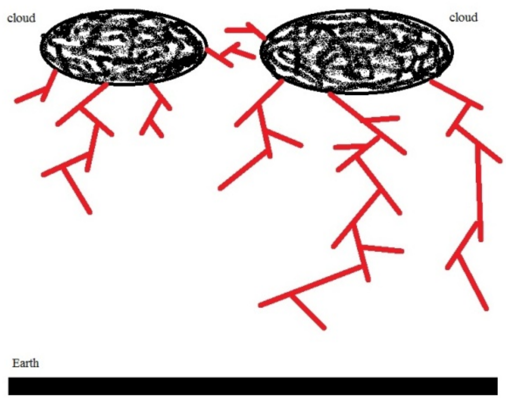

Fig. 1. Illustration of the striking propagation

Many previous works have been reported since Benjamin Franklin initiated the striking power from sky throughout the cloud charge within the eighteenth century as the Fanklin's Time for understanding the lightning flash related to the electrical nature. Various characteristics have been observed and tested for analyzing these curious issues in many studies in order to recognize natural behaviours [17]-[25]. Furthermore, a seat of electrical processes can be produced by a thunderstorm associated with the result of air convection combined with substantial humidity. In particular, studies of thunderstorms have rapidly advanced during the past century and many efforts have been made towards for understanding the multiple lightning, thunderstorms, and their consequences. Recently, observations of the phenomena on an active lightning discharge with data collection and data analysis have renewed interest in the field of thunderstorms and their consequences in the biosphere. Technically, thunder is defined as the sound made by a lightning presented in a sharp; a loud crack; and a low rumble, caused by the rapid expansion of air. In nature, thunderstorms affect relatively small areas when compared with hurricanes, despite their small size but all thunderstorms are dangerous. Specifically, a thunderstorm can be recognized like a cotton mob or a puffy shape expanded to begin growing upwards of the potential striking path. In this phenomenon, defining atmospheric materials for the thunderstorm is very important things and urgently observations covered in moisture; unstable air; and lift. These materials should be detected and mitigated for knowing all processes of the existing thunderstorm mechanism. In detail, the moisture is consisted of water in the atmosphere to form clouds and rain. The unstable air is supported by warm air to contrast with the air surrounding the clouds in order to unstable air will cause the cloud to increase quickly. The lift is provided by warm or cold fronts, sea breezes, mountains or other phenomenon.

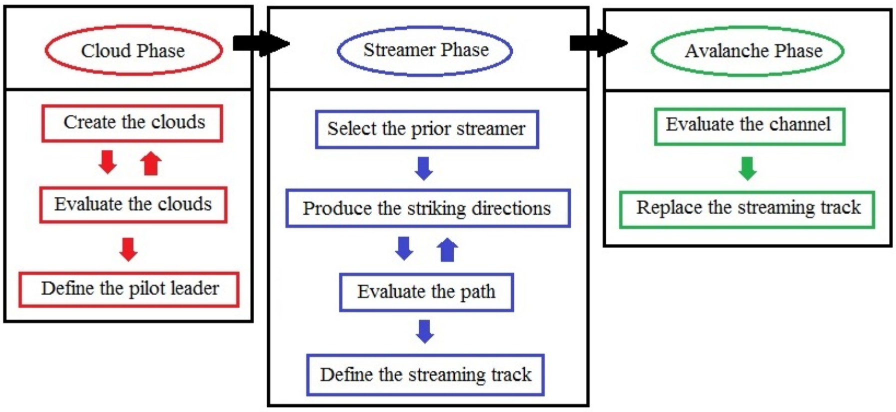

Fig. 2. Hierarchy processes of thunderstorm algorithm

By considering this phenomenon, its mechanisms are adopted to become an intelligent computation for pretending its processes in nature as presented in this section. These mechanisms are performed using several stages to explain the adoption in computing procedures as a new evolutionary algorithm namely TA based on the natural inspiration of the thunderstorm as illustrated in Fig. 2. In particular, the searching mechanism for selecting solution is conducted to striking processes and channelling avalanches for releasing the charges. In addition, the cloud charge is populated using a certain procedure for the possibility clouds as given in (1). Moreover, TA is also consisted of various distances of the streamer deployed by a hazardous factor for distributing positions of the striking targets as presented in (2). Each solution is located randomly based on the generating random directions of multiple striking sources. According to Fig. 2, TA is executed using several steps for defining and selecting the optimal solution. The generating population set is initiated on the first step as the cloud charge associated with many technical constraints and limitations. In principle, the sequencing computation of TA is given in several procedures as the pseudo-codes in terms of Cloud Phase: Streamer Phase; and Avalanche Phase. Cloud Phase is used to produce the cloud charges, and to evaluate the clouds before defining the pilot leader. Another step, Streamer Phase, is implemented to select the prior streamer and to guide the striking directions included the path evaluation for defining the streaming track. The final process is Avalanche Phase used to evaluate the channels, replace the streaming track for keeping the streamer. Mathematically, these main functions are presented as follow:

Cloud charge: $Q_{sj}^{m} = (1 + k.c).Q_{midj}^{m}$, (1)

Striking path: $D_{sj}^{n} = (Q_{sdep}^{n}).b.k$, (2)

Charge's probability: $probQ_{sj} \begin{cases} \frac{Q_{sj}^{m}}{\Sigma Q_{s}^{m}} \text{ for m} \\ \frac{Q_{sj}^{n}}{\Sigma Q_{s}^{n}} \text{ for n} \end{cases}$, (3)

where Q_{sj} is the current charge, Q_{midj} is the middle charges, s is the streaming flow, D_{sj} is the striking charge's position, Q_{sdep} is the deployed distance, n is the striking direction of the h^{th}, k is the random number with [-1 and 1], c is the random within [1 and h], h is the hazardous factor, b is the random within (1-a), n is the striking direction, j ∊ (1,2,..,a), a is the number of variables, m ∊ (1,2,..,h).

III. ECONOMIC ASSESSMENT

Practically, a power system is developed using integrated enterprises for providing and delivering electric energy from generator sites to some areas of load centres, which is supported by some physical components to create an interconnection system consisted of generation; transmission and sub transmission; distribution and utilization [2]. Moreover, these integrated structures of the power system are built for a large interconnection of electric networks with joining all various types of generating units. This interconnection is also used to serve all demands at different places using transmission and distribution lines in long distances for supplying energy with the high quality and reliable power productions. In addition, energy should be transferred to users with the lowest possible cost while satisfying various constraints imposed in the system. Technically, the total power output of generating units is produced using a committed power schedule at a certain period time operation to share a generated capacity considered fuel consumptions and public awareness of the environmental protection for reducing atmospheric emissions [1]-[5]. The environmental protection requirements have also forced to consider the emission from combustions of fossil fuels at thermal power plants [3], [4]. In addition, combustions of fossil fuels at thermal power plants have contributed to produce pollutant emissions in various types [1]-[5].

These emissions are associated with its scheduled power outputs while supporting the committed power production to meet the load demand.

Currently, fuel costs and pollutant compensations become important things in the power system operation since the power system operation is focused on the technical cost of products and services [1], [2], [13]. The optimal operation and planning of power generations have occupied an important position in the electric power industry considered its combination for decreasing pollutant productions and reducing fuel consumptions throughout a problem using penalty and compromised factors for obtaining the balance power output schedule. These problems become important works to decrease running charges of electric energy measured economically using a minimum total cost for establishing the whole operations considered operational constraints to obtain a better combination of scheduled generating units. This strategy is commonly performed by a minimized total fuel cost of generating units while producing the total power output throughout an economic dispatch (ED) problem for fuel consumptions [8]-[13]. This economic strategy is also used to decide the optimal operating cost for the given load with decreasing the total pollutant production throughout emission dispatch (EmiD) at every period time operation [5].

By considering ED and EmiD problems, the dispatching problem treats impacts of both aspects as the single objective of the optimization scenario which is required by some targets to reach a reasonable solution in feasible ranges of the operation. It is also used for optimizing the total cost of fuel consumptions and the total pollutant emission compensation of generating units [15]. Both dispatches are converted to become an integrated dispatch problem (IDP) consisted of economic and emission dispatches with the main orientation for existing the interconnected structures to deliver electric energy from generator sites to energy users with considering technical constraints and environmental requirements. Basically, the IDP considers the total fuel cost as shown in (5) with embedding an individual fuel cost of each generating unit online the power system. It also adopts the environmental protection as the total pollutant production included in generating unit operations. Its discharge is used for measuring the pollutant effect as given in (6) for the emission problem. Shortly, the IDP is expressed in (4) as the single objective function of the economic assessment for the power system operation considered the ED and EmiD.

$$\text{IDP: } \Phi_t = w.F_t + (1-w).h.E_t, \tag{4}$$

$$\text{Fuel: } F_t = \sum_{i=1}^{ng}(c_i + b_i.P_i + a_i.P_i^2), \tag{5}$$

$$\text{Pollution: } E_t = \sum_{i=1}^{ng}(\gamma_i + \beta_i.P_i + \alpha_i.P_i^2), \tag{6}$$

where Φ_t is the IDP, w is a weighting factor, h is a penalty factor, F_t is the total fuel cost of generating units (\$/hr), a_i; b_i; c_i are coefficients of the quadratic fuel cost by the i^{th} generating unit, P_i is the power output of the i^{th} generating unit, ng is the number of generator, E_t is the total emission discharge of generating units (kg/hr), α_i; β_i; γ_i are coefficients of emission characteristics by the i^{th} generating unit.

As mentioned before, the power system is commonly established using main sections covered in generation; transmission; distribution and utilization. In this integration, a saving in the power system operation represents a significant effort for reducing the total operating cost as well as in the quantities of fuel consumptions. This effort also represents the pollutant reduction while providing electric energy from the thermal power plants to meet the total demand at all periods for the emission production. To support this effort, technical constraints and environmental requirements have to take double attentions for deciding a reasonable operating cost. In these works, the IDP is desired to search the optimal solution considered several technical limitations in terms of power limits; voltage fluctuations; power transfer capability; and power balance as following statements:

$$\text{Active power: } P_i^{min} \le P_i \le P_i^{max}, \tag{7}$$

$$\text{Reactive power: } Q_i^{min} \le Q_i \le Q_i^{max}, \tag{8}$$

$$\text{Voltage: } V_p^{min} \le V_p \le V_p^{max}, \tag{9}$$

$$\text{Power transfer: } S_{pq} \le S_{pq}^{max}, \tag{10}$$

$$\text{Power balance: } \sum_{i=1}^{ng} P_i = P_D + P_L, \tag{11}$$

where P_i is a output power of the i^{th} generating unit, P_i^{min} is a minimum output power of the i^{th} generating unit, P_i^{max} is a maximum output power of the i^{th} generating unit, Q_i^{max} and Q_i^{min} are maximum and minimum reactive powers of the i^{th} generating unit, V_p^{max} and V_p^{min} are maximum and minimum voltages at bus p, S_{pq} is a total power transfer between bus p and q, S_{pq}^{max} is a limit of power transfer between bus p and q, P_D is the total demand, V_p is a voltage at bus p, P_L is the total transmission loss, and ng is the number of generating units.

IV. SAMPLE SYSTEM AND PROCEDURES

To cover this assessment, designed programs for searching solutions of the IDP on the power system operation is revered to Fig. 2. This figure illustrates that TA is consisted of several steps associated with its phases on the computation. In particular, this simulation uses a standard model from Institution of Electrical and Electronics Engineers (IEEE) as a sample system for demonstrating the economic assessment and performing the searching guidance of TA. As many previous studies used standard models, these works also adopt the standard technical data associated with the IEEE-62 bus system model as the tested system with its parameters are 62 buses; 89 lines; and 32 load buses, as detailed in [15] and provided partly in Table I for approaching thermal power plants as interconnected generating units with coefficients and limits of the operations.

TABLE I. Fuel Cost and Emission Coefficients of Generating Units

Bus	Gen	a, x10^{-3} (\$/MWh^2)	b (\$/MWh)	c	α (kg/MWh^2)	β (kg/MWh)	γ	Real (MW)		Reactive (MVar)	
								Min	Max	Min	Min
1	G1	7.00	6.80	95	0.0180	-1.8100	24.300	50	300	0	450
2	G2	5.50	4.00	30	0.0330	-2.5000	27.023	50	450	0	500
5	G3	5.50	4.00	45	0.0330	-2.5000	27.023	50	450	-50	500
9	G4	2.50	0.85	10	0.0136	-1.3000	22.070	0	100	0	150
14	G5	6.00	4.60	20	0.0180	-1.8100	24.300	50	300	-50	300
17	G6	5.50	4.00	90	0.0330	-2.5000	27.023	50	450	-50	500
23	G7	6.50	4.70	42	0.0126	-1.3600	23.040	50	200	-50	250
25	G8	7.50	5.00	46	0.0360	-3.0000	29.030	50	500	-100	600
32	G9	8.50	6.00	55	0.0400	-3.2000	27.050	0	600	-100	550
33	G10	2.00	0.50	58	0.0136	-1.3000	22.070	0	100	0	150
34	G11	4.50	1.60	65	0.0139	-1.2500	23.010	50	150	-50	200
37	G12	2.50	0.85	78	0.0121	-1.2700	21.090	0	150	0	75
49	G13	5.00	1.80	75	0.0180	-1.8100	24.300	50	300	-50	300
50	G14	4.50	1.60	85	0.0140	-1.2000	23.060	0	150	-50	200
51	G15	6.50	4.70	80	0.0360	-3.0000	29.000	0	500	-50	550
52	G16	4.50	1.40	90	0.0139	-1.2500	23.010	50	150	-50	200
54	G17	2.50	0.85	10	0.0136	-1.3000	22.070	0	100	0	150
57	G18	4.50	1.60	25	0.0180	-1.8100	24.300	50	300	-50	400
58	G19	8.00	5.50	90	0.0400	-3.000	27.010	100	600	-100	600

For demonstrating performances of TA, in these works, this novel algorithm is executed using its parameters covered in the loss limit is 10%; the weighting factor is 0.5; the emission standard is 0.85 kg/h; the avalanche is 1; the maximum cloud charge is 50; the maximum striking is 100; and the hazardous factor is 6. This simulation also covers its technical criteria as presented in (7) to (11) in order to search the suitable solution within constraints and requirements.

V. RESULTS AND DISCUSSIONS

In this section, the evaluation is addressed to assess the optimal solution of the IDP considered operational constraints and the environmental requirement focused on the power plants for reducing pollutant productions and decreasing operational costs. In particular, pollutant productions are forced by the environmental requirement to control gaseous discharges in various types as the effect of fossil fuel combustions at thermal power plants. In these studies, TA uses six striking targets randomly for convey the cloud charges within all periods for creating the channel. This simulation also considered all defined technical constraints and thunderstorm phases for providing energy in order to meet 2,912 MW and 1,269 MVar of the total load demand at customer areas as presented using the IEEE-62 bus system model for the integrated power system.

A set population is given in the Cloud Phase throughout the cloud charges as presented in Fig. 3 with considering power constraints of generating units included the other technical requirements for its evaluation. These charges are created for G1 to G19 in various positions as 50 candidate solutions for every streaming cycle with the convergence speed as illustrated in Fig. 5. In addition, Fig. 4 shows characteristics of the IDP in the progressing individual combination of power plants as given in the unit commitment with real defined power outputs as presented in Fig. 8 for 19 generating units. As illustrated in Fig. 5, the convergence speed is obtained in 14 steps with fast and smooth characteristics. Furthermore, time consumptions of TA for every streaming flow are depicted in Fig. 6 with its random characteristic to remain the solution is searched totally in 54.1 s for all steps. Moreover, by concerning in the Streamer Phase, the striking targets are conditioned using 6 of hazardous factors for every process with its possibility cloud charges in the streaming tracks. In detail, Fig. 7 shows the six streaming tracks of striking positions which are combined in various directions for generating further striking points in random distances and positions.

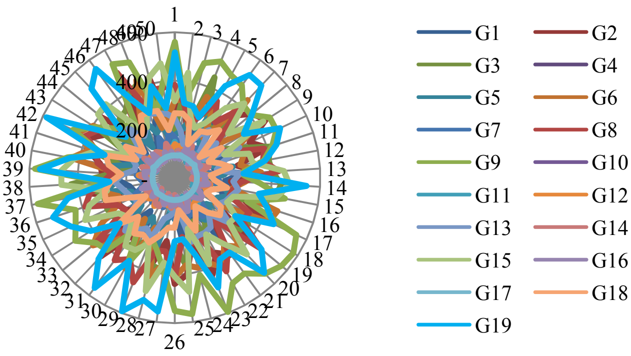

Fig. 3. Distribution of the cloud charges

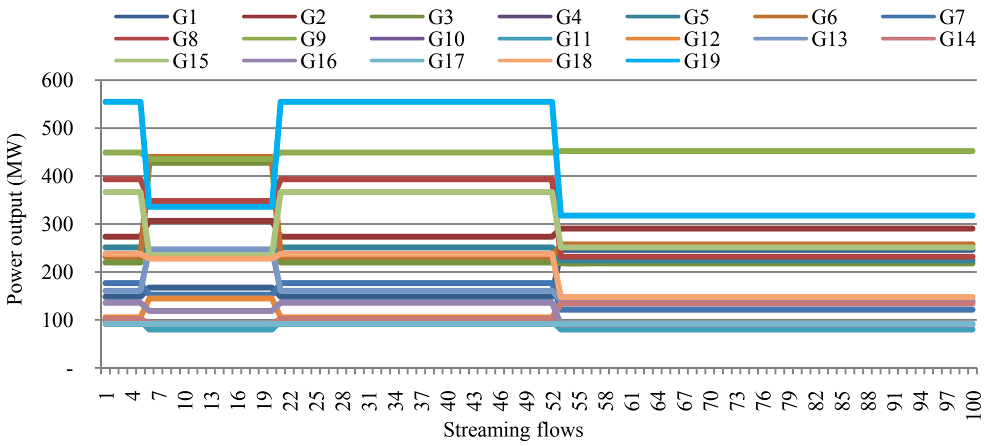

Fig. 4. Progressing individual solution

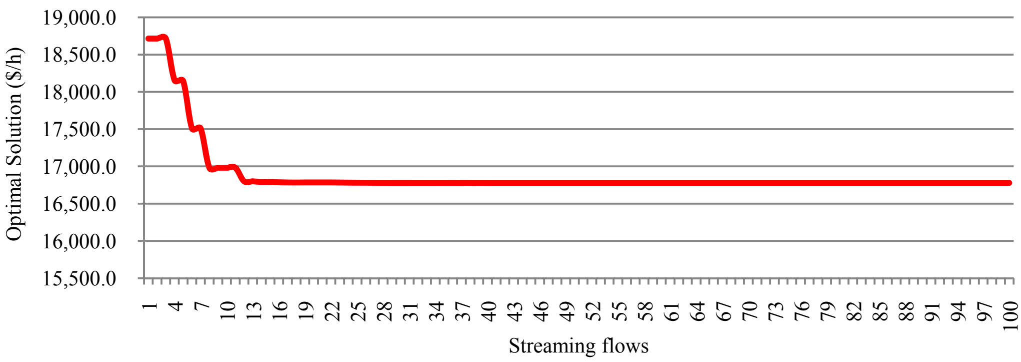

Fig. 5. Convergence speed characteristic

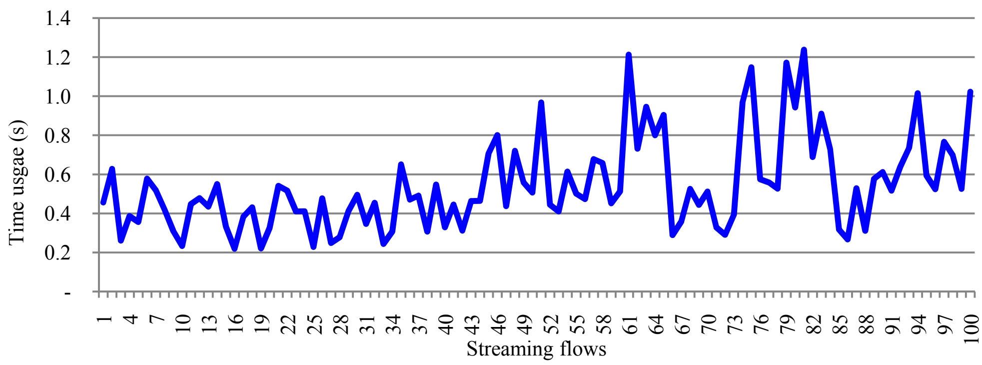

Fig. 6. Time consumption characteristic

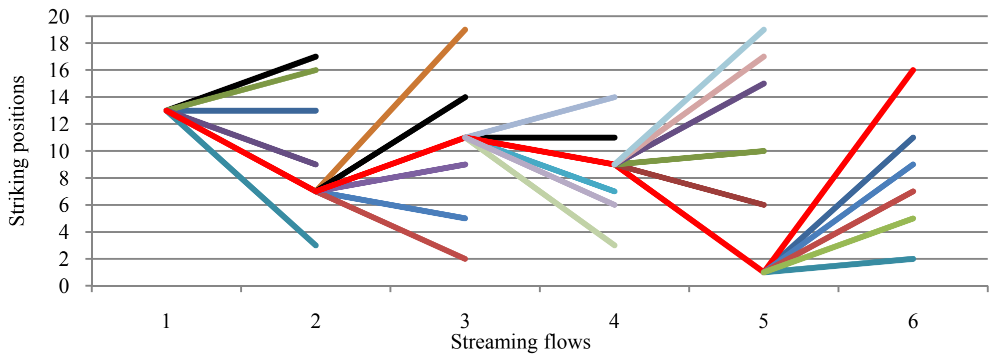

Fig. 7. The streaming tracks of six striking positions for 6 flows early

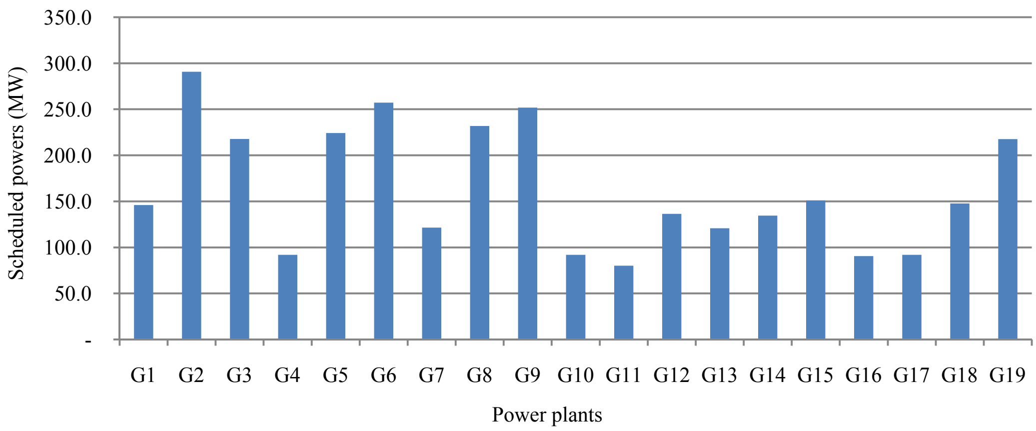

Fig. 8. Power output combination

TABLE II. Power and Pollutant Productions of Power Plants

Gen	Scheduled Power Output (MW)	Operational Power Portions (%)	Produced Emission (kg/h)	Permitted Emission (kg/h)	Undischarged Emission (kg/h)
G1	146.0	4.7	143.8	124.1	19.7
G2	290.7	9.4	2,088.6	247.1	1,841.5
G3	217.7	7.0	1,047.1	185.1	862.0
G4	91.9	3.0	17.5	78.1	-
G5	224.2	7.2	523.4	190.6	332.8
G6	257.3	8.3	1,567.8	218.7	1,349.1
G7	121.6	3.9	43.9	103.3	-

G8	231.9	7.5	1,268.8	197.1	1,071.8
G9	251.9	8.1	1,759.1	214.1	1,545.0
G10	91.9	3.0	17.5	78.1	-
G11	80.1	2.6	12.1	68.1	-
G12	136.4	4.4	72.9	115.9	-
G13	120.8	3.9	68.2	102.7	-
G14	134.6	4.3	115.1	114.4	0.7
G15	151.0	4.9	397.2	128.4	268.8
G16	90.5	2.9	23.7	76.9	-
G17	91.9	3.0	17.5	78.1	-
G18	147.7	4.8	149.7	125.5	24.1
G19	217.6	7.0	1,268.1	185.0	1,083.1
Total	3,095.7	100.0	10,602.0	2,631.3	8,398.6

As illustrated in previous figures that TA has ability to search the final solution with fast and smooth included the short time consumption for completing the computation, this implementation is subjected to assess thermal power plants on the integrated power system using the IEEE-62 bus system with targeting for decreasing the pollutant production and reducing the operational cost. Real productions of power plants are provided in Table II covered in terms of power outputs and pollutant contributions for 19 existed generating units as the unit commitment to serve the load demand. From this table, it is known that all contributors supported in different capacities while serving 2,912 MW by 3,095.7 MW totally with the total loss around 5.9% or 183.5 MW. This unit commitment also produced pollutants in various amounts for each generating units even it took a place in numerous portions with discharging the total emission in 2,631.3 kg/h as the permitted pollution. By considering the all producers, the pollution should be stored in 8,298.6 kg/h as the effort of an environmental protection in air from the total emission of 10,602.0 kg/h.

TABLE III. Operating Cost of Power Plants

Gen	Emission			Fuel Fees ($/h)	Total Fees ($/h)
	Produced Fess ($/h)	**Permitted Fees ($/h)**	**Undischarged Fess ($/h)**		
G1	53.2	45.9	7.3	150,299.8	150,307.1
G2	772.8	91.4	681.4	465,978.5	466,659.9
G3	387.4	68.5	318.9	261,578.9	261,897.8
G4	6.5	28.9	-	21,202.1	21,202.1
G5	193.7	70.5	123.1	302,645.2	302,768.3
G6	580.1	80.9	499.2	365,237.3	365,736.5
G7	16.2	38.2	-	96,726.2	96,726.2
G8	469.5	72.9	396.6	404,537.6	404,934.1
G9	650.9	79.2	571.7	540,922.1	541,493.7
G10	6.5	28.9	-	16,995.2	16,995.2
G11	4.5	25.2	-	29,065.2	29,065.2
G12	27.0	42.9	-	46,706.3	46,706.3
G13	25.2	38.0	-	73,255.6	73,255.6
G14	42.6	42.3	0.3	81,827.6	81,827.8
G15	147.0	47.5	99.5	148,996.2	149,095.7
G16	8.8	28.5	-	37,072.8	37,072.8
G17	6.5	28.9	-	21,202.1	21,202.1
G18	55.4	46.4	8.9	98,430.1	98,439.0
G19	469.2	68.5	400.7	380,084.9	380,485.6
Total	**3,922.7**	**973.6**	**3,107.5**	**3,542,763.7**	**3,545,871.2**

Table III shows other results of the assessment on the thermal power plants as approached using the IEEE-62 bus system model in financial fees covered in terms of fuel consumptions and emission compensations. From this table, it can be seen that each generating units need different budgets for joining in the integrated power system with its compensations for individual pollutant discharges. In total, the IDP obtained in 3,545,871.2 \$/h for operating cost while serving 2,912 MW of the load demand with 3,542,763.7 \$/h of the fee used for providing the fuel. In addition, the unit commitment of power outputs from generating units need to compensate the emission around 3,107.5 \$/h considered the emission standard and it spend around 3,922.7 \$/h for the emission if it should be reduced to zero pollutants.

VI. CONCLUSIONS

This paper introduces the novel intelligent computation namely Thunderstorm Algorithm to assess thermal power plants on the integrated power system with various technical constraints included an emission standard. By using six hazardous factors, simulations showed that TA has ability to search the solution in the fast convergence speed with smooth and quick to select the optimal solution. The proposed method of TA seems strongly to be a new promising approach for solving an integrated dispatch problem based on the solution quality and the computational efficiency under several constraints. From these works, real system applications are recommended to the further future investigation as same as various aspects of TA on the computation needed to observe more.

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