Multi-Area Economic Dispatch Considering Generation Uncertainty

M. J. Mokarram, M. Nayeripour, T. Niknam, E. Waffenschmidt

***Abstract*— Multi area economic dispatch (MAED) problem are one the important issues in operation management of modern electric power systems with the distributed geographically areas. In this case, preserving power network information plays an important role in the MAED problem which should be taken into consideration in this possess. For this purpose, a new hierarchal process is used in such a way that the load is supplied while the information security is preserved. In addition, the effect of wind turbines (WTs) uncertainty is studied to simulate real scenarios. Monte Carlo Simulation (MCS) technique is used to consider the effect of uncertainty in the MAED problems. Finally, the JAYA algorithm is utilized to find the optimal solution of the MAED problems.**

***Index Terms*— uncertainty, Hierarchal Multi Area Economic Dispatch, MCS, JAYA Algorithm.**

I. INTRODUCTION

In recent years, multi area economic dispatch (MAED) as a new extension of economic dispatch (ED) is highly recommended in the modern power networks. In this case, different areas are electrically connected to each other to improve the technical and economical aspect of power networks. In fact, some areas may cannot supply their demanded load with an acceptable reliability, however, other areas can compensate the lack of generation to the area through tie-lines in shortage. In addition, the value of the cost function will be improved by connecting areas to each other [1].

Corresponding author, M. Nayeripour is with the Cologne University of Applied Science and AvH Foundation, Germany. (Email: majid.nayeripour@th-koeln.de)

M.J. Mokaram and T. Niknam are with the Department of Electrical Engineering, Shiraz University of Technology, Shiraz, Iran (Emails: m.j.mokarram@gmail.com, niknam@sutech.ac.ir)

E. Waffenschmidt is with Cologne University of Applied Science, (Email: Eberhard.waffenschmidt@th-koeln.de)

ED problems are generally performed to find the proper output of generators in such a way that the demanded load is supplied while the technical constraints are met. Moreover, the MAED includes some areas which are connected to each other through some tie-lines. One of the most important features of MAED is to preserve information security as another important constraint in which plays an important role. The only exchanged information between areas are the amount of tie-lines' power and other areas do not have access to all the information. Hence, the main challenge in the MAED problems are identifying the proper output of each generators and also, the proper exchanged power between areas in such a way that the demanded load in all areas are supplied while the technical constraints are satisfied.

The MAED problems are generally more complex than the ED ones due to more sophisticated constraints, so a powerful method is vitally necessary to solve them. Thus, two types of approaches including gradient based and metaheuristic methods were used in the literatures.

Most articles try to concentrate on proposing a method to identify how to coordinate areas in the MAED problems in such a way that the information security is preserved. Thus, in order to solve the problem of MAED easily, the mentioned literatures, suppose that the cost function is smooth and convex. In this case, mathematical methods are the best choice to find the optimal solution in such problems. For instance, the linear programming in [2], Dantzig–Wolfe decomposition principle in [3] and decomposition approach using expert systems in [4] have been utilized to solve MAED problem.

The important point in this issue is that the power plant cost function versus active power is non-convex and non-smooth due to valve point effect and multi-fuel generators. In this case, the mathematical methods in which the gradient methods are utilized no longer can solve the MAED problems.

In the case that the MAED is considered as a non-smooth and non-convex problem, some meta-heuristics methods were proposed like the PSO with reserve-constrained multi-area environmental/economic dispatch [5], the new nonlinear optimization neural network approach [6], the artificial bee colony optimization [7], the teaching-learning based optimization (TLBO) [1] and the chaotic global best artificial bee colony [8]. JAYA algorithm as a simple algorithm has been introduced to find optimal solution in the non-smooth and non-convex optimization problems. Therefore, it can be a promising candidate to solve MAED problems. Also, a hierarchal process is used to consider the equality constraint while the information security is preserved.

More constraints have been created in presence of increased penetration level of distributed generations (DGs) in different area of system while they have some important features. In this case, despite all benefits of DGs and specially wind turbines (WTs), the outputs' fluctuation due to uncertainty arising from their behaviors makes utilizing of them difficult. It means that, the output of these renewable energy power plants has a probability distribution function (PDF) instead of an exact value. Therefore, a probability density function is introduced to clarify the happing's probability of each point. In this case, the main question is that "what is the exact output's value and how to consider the effect of uncertainty in the output? "

The effect of uncertainty has been studied with different methods in literatures [9]. Monte Carlo simulation (MCS) as the most well-known simulation method has been used in a wide range of literatures [9]. Although, the MCS are a simple system-dimension independent method, it demands a huge number of simulations.

In this research, considering wind energy as one of the clean renewable energy resources, the MAED problems are applied to the system which is mainly supported by this clean resource. In this way, the WT's uncertainty is considered. To do this, MCS method is used in the paper. The effectiveness of the MCS method has been proved in the literatures [10]. Moreover, in the MAED problem, the demanded load is supplied while the exchanged power between areas constraints is met through a hierarchal method. In addition, in order to obtain the optimal solution of the HMAED problems, we used a JAYA algorithm. The effectiveness of JAYA method is tested through dimensionally different cases.

II. Multi-area economic dispatch

Economic dispatch (ED) problem, as a predominate subject in the power system domain, the aim is to identify the best output of each generator not only to have economically cost but also to consider all the operational and technical constraints meaning that the ED problem is an optimization problem.

In the ED problems, cost function is the fuel expense with a second degree polynomial according to (1) and finding its minimum value is vitally necessary. In addition, equality constraint tries to supply demanded load (2), while, inequality constraint is the generation boundary of each generator (3) which is called power balance constraint.

$$F = a \times p_g^{2} + b \times p_g + c \tag{1}$$

$$\sum_{i=1}^{N_g} P_{gi} = P_D + P_L \tag{2}$$

$$P_{gi\,\min} \le P_{gi} \le P_{gi\,\max} \tag{3}$$

Although, this version of the generator's cost function is convex and smooth and its minimum value can be find by gradient based methods, it is not an exact model and is not more applicable in the huge steams' generators. In fact, in the steam generators a lot of valves have to be opened to increase the output power. The mechanical losses of the valves make the cost function non-smooth and non-convex. In order to consider the effect of valve point, a sinusoidal term has to be added to the equation (1). Moreover, the equation (4) represents the cost function of each generator in terms of active power while valve point effect (VPE) is considered:

$$\begin{aligned} F = a \times p_g^{2} + b \times p_g + c + \\ |\, e \times \sin(f \times (p_{g\min} - p_g))\,| \end{aligned} \tag{4}$$

In addition, Fig. 1 shows the cost function of a sample generator with and without VPE.

The non-convex points lead to more local minima. Also, the gradient is not defined in these points, meaning that the slope in the both side of them are vary. Thus, using a powerful method which not only can handle the non-convex problems but also, does not stick in the local minima is vitally necessary.

As it is stated before, the MAED is an extended ED problem. In this case, MAED includes some areas that they connect to each other to decrease fuel cost, effect of contingency, etc. In this case, any area consists load, and generators. The system operators (SOs) send a few information to other areas and other areas do not have access to the rest of information. It means, SOs must find the output of each generators and exchanged power by a few information from other areas. In fact, just a few information of other areas which are tie-line exchange power amounts are available. Fig. 2 shows a sample power networks which includes four areas and they are connected together through six tie-lines.

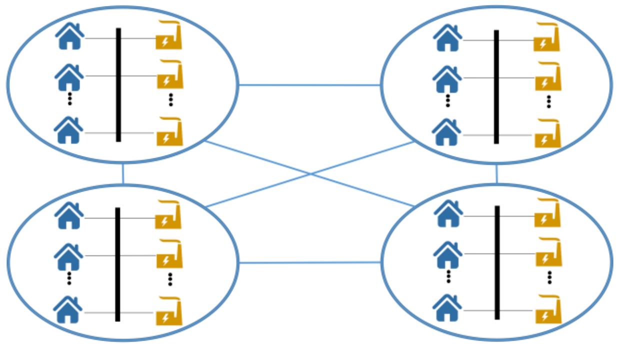

Fig 2. Four areas are connected together through six tie-lines

In MAED, the cost function in all areas has to be minimized, while the equality and inequality constraints which are more complicated than the ED ones are met. The cost function formulation, equality and inequality constraints in the MAED problem are shown in the equations (5)–(14).

$$Min\ C(X) = \sum_{i=1}^{M} \sum_{j=1}^{Ngi} F_{ij}(P_{gij})$$

$$F_{ij}(P_{gij}) = a_{ij} \times P_{gij}^{2} + b_{ij} \times P_{gij} + c_{ij} + | e_{ij} \times \sin(f_{ij} \times (P_{gij\ \min} - P_{gij})) | \quad (5)$$

$$X = [\vec{P}_g, \vec{T}] \quad (6)$$

$$\vec{P}_g = [\vec{P}_{g1}, \vec{P}_{g2}, \vec{P}_{g3}, \dots, \vec{P}_{gM}] \quad (7)$$

$$\vec{P}_{gi} = [P_{gi1}, P_{gi2}, P_{gi3}, \dots, P_{giGi}] \ \ i = 1,2,\dots,M \quad (8)$$

$$\vec{T} = [\vec{T}_1, \vec{T}_2, \dots, \vec{T}_M] \quad (9)$$

$$[\vec{T}_1, \vec{T}_2, \dots, \vec{T}_M] = [\, [T_{1,1}, T_{1,2}, \dots, T_{1,M}], [T_{2,3}, T_{2,4}, \dots, T_{2,M}], \dots, [T_{M\text{-}1,M}]\,] \quad (10)$$

$$P_{gij\min} \le P_{gij} \le P_{gij\max} \quad (11)$$

$$-T_{ij\max} \le T_{ij} \le T_{ij\max} \quad (12)$$

$$\vec{P}_{Li} = \sum_{q=1}^{N_{gi}} \sum_{j=1}^{N_{gi}} P_{gij}\ B^{i}{}_{qj}\ P_{giq} + \sum_{j=1}^{N_{gi}} B^{i}{}_{0j}\ P_{gij} + B^{i}{}_{00} \quad (13)$$

$$\vec{P}_{gi} = \vec{P}_{Di} + \vec{P}_{Li} + \sum_{j=1, j\neq i}^{N} T_{ij} \qquad i = 1,2,\dots,M \quad (14)$$

Where P_{gij} *and* T_{ij} are decision variables, while the $B^{i}{}_{0j}$ is The loss coefficient associated with producing of the j^{th} generator in area i and $B^{i}{}_{00}$ is The loss coefficient parameter (MW) in area *i*.

Where (5) shows the non-smooth and non-convex cost function of MAED problem considering VPEs. In addition, the equations (6), (7), (8), (9), and (10) depict the decision variables in the MAED problem. As shown in the (6), the output of MAED problem includes tie-line exchange power and output power.

Inequality constraints in the MAED problems are power output (11) and tie-line constraints (12). In addition, equations (13), and (14) represent the equality constraint in the MAED problems meaning that the output power of each generator must be well determined in such way that demanded load and transmission losses (13) is supplied.

III. PROBABILISTIC MULTI-AREA ECONOMIC DISPATCH

The MCS technique have been well-known dealing with uncertainties in engineering problems which consider the almost possible scenarios. This method generates random sets of numbers from specified PDF in which are involved in a problem. Then, the generated numbers undergo general model, herein equation (5). Eventually, the statistical quantities (Mean and standard deviation (STD)) of the system output, here cost function, would be assessed according to (15) and (16). The MCS is an appropriate choice when the model is complicated, nonlinear, and when there are a lot of uncertain parameters such as MAED.

$$Mean = \frac{1}{H} \sum_{i=1}^{H} F_i \quad (15)$$

$$STD = \sqrt{\frac{1}{H-1} \sum_{i=1}^{H} (F_i - Mean)^2} \quad (16)$$

Where *H* is the number of simulations in the MCS method.

IV. JAYA ALGORITHM

The JAYA algorithm as a new and sample meta heuristic algorithm was introduced by "R. Venkata Rao" [11]. In order to find optimal solution, this algorithm suggest that the individuals must move towards the best solution and keep out the worst solution, simultaneously. Moreover, the equation (17) represents the process of JAYA method.

$$X^{new} = X + r_1 (X - | X |) - r_2 (X - | X |) \quad (17)$$

V. HIERARCHAL PROCESS

In the hierarchal process, not only the MAED constraints are met, but also information security is preserved. It is worth

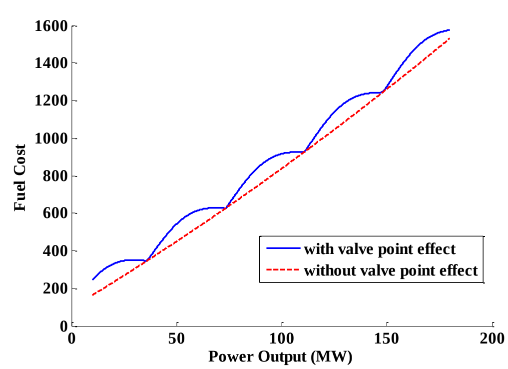

Fig 1. Fuel cost of a sample generator with/without VPEs

mentioning that the decision variables including output power and tie-line's exchanged power are control variables. It means that it is possible to fix them on the boundary condition. In addition, the next steps describe the preserving information security which proposed in this paper.

Step1: Select an area randomly

Step2: Specify the new demanded load based on the input and output exchanged power related to this area as follow:

$$P_{Li}^{new} = P_{Li}^{old} + \sum_{j=1}^{M} Tij$$

Step3: Calculate the s_i

$$s_i = \sum_{j=1}^{N_{gi}} p_{gij}^{\max} - P_{Li}^{new}$$

Step4: Satisfy the Area Capability Constraint (ACC)

Given the fact that an area cannot send electric power more than the s_i, the tie-lines exchanged power is changed to satisfy the constraint. In fact, there are two modes to happen for the ACC constraint which are discussed in the following:

1) The generated power in one area is less than demanded power ($\sum_{j=1}^{Ngi} P_{gij}^{\max} - P_L < 0$)

For this case, considering the tie-line capacity constraint, the net transmitted power by connected tie-lines must be between $\sum_{j=1}^{Ngi} T_{ij\min}$ and $(\sum_{j=1}^{Ngi} P_{gi}^{\max} - P_{Li})$.

2) The generated power in one area is more than demanded power ($\sum_{j=1}^{Ngi} P_{gij}^{\max} - P_L > 0$)

In this case, the net transmitted power by the connected tie lines must be between $(\min\left\{(\sum_{j=1}^{Ngi} P_{gi\max} - P_{Li}), \sum_{j=1}^{M} T_{ij\max}\right\})$ and $\sum_{j=1}^{M} T_{ij\min}$ when the tie-line capacity constraint for each of them was satisfied.

Step5: *Equality constraint of the load and power generation for the selected area must be satisfied.*

Step6: Check the finishing criteria

If all areas are selected, then go to calculate cost function. Otherwise select another area randomly and go to step 2.

VI. Simulation Results

The random nature and uncertainty factors in optimization process create some challenges for the SOs. In this paper, the generation uncertainty is considered in the MAED problems.

The effect of the uncertain parameters through some situations in two different dimensional case studies are studied and the characteristic of them are represented below.

The Weibull and normal distribution functions can be used for the wind's uncertainty. In this paper, for the sake of simplicity, the normal distribution function is selected for wind uncertainty model. The coefficient of variation (COV) of wind energy are chosen at 10%.

$$COV = \frac{STD}{Mean}$$

In order to demonstrate the effectiveness and applicability of MCS in the HMAED problems, it is applied on different cases. For a quick reference, these cases are given in Table I.

TABLE I. SIMULATION CASE STUDIES

	Number of generators (case information)
Case1	Two areas includes Six generators
Case2	Three areas includes Ten generators

All simulations are run by using MATLAB 8.3 on a Laptop (2.6 GHz, 8 GB RAM).

First case) six generators in two areas

In this case, there are six generators which are distributed in two areas. The demanded load for the first area is 758.7MW, while it is 505.2MW for the second area. The areas are connected through one tie-line where the transmission capacity of this tie-line is $\pm 100MW$. The rest of the information about the generators is presented in [1]. It is assumed that the third generator in the first and second area are replaced with two WTs that their Means are 150, and 70, respectively. In our simulation, MCS has been implemented for 5000 times and the convergence curve of Mean and STD of results are shown in the Fig. 3 and Fig. 4. The simulation results show that MCS yields the accurate results through multiple simulations.

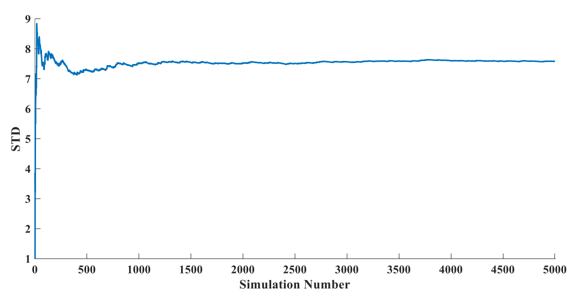

Fig. 3. The STD output for the first case

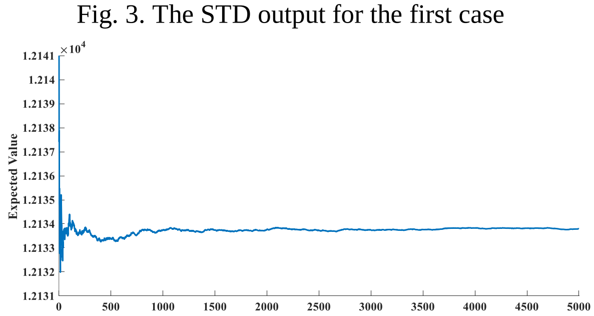

Fig. 4. The expected value output for the first case

Second case) ten generators in three areas

Considering the multi-fuel generators in real situations, the MAED problems will be more complex. The generators cost coefficients are varied because different sorts of fuels such as coal, natural gas, and oil are utilized. It is essential to choose the right fuel type to economize efficient cost. In order to consider the multi-fuel generators, an MAED problems with ten generators which are distributed in three areas is selected. In addition, the demanded load for the first area is 1350MW, while it is 675MW for the second and also third area. Moreover, first, second, and third areas contain four, three, and three generators which are utilizing different type of fuels, respectively. The areas are connected to each other through three tie-lines which the capacity of them is $\pm 100MW$. considering the multi-fuel generators and also the VPE which brings about non-convexity and non-smoothness, this case is a complex and sophisticated one in the MAED problems. The Mean and STD of uncertain WTS which are considered in this case are given in Table II.

TABLE II. THE CHARACTERISTIC OF WTS WHICH IS USED IN THE SECOND CASE

Area	Mean	STD	Uncertain generator
First area	200	20	Second
Second area	150	15	Second
Third area	100	10	First

The expected and STD convergence curve are displayed in the Fig. 5 and Fig. 6. These curves show also the accuracy of MCS method to follow the expected value and STD after about 2000 iteration.

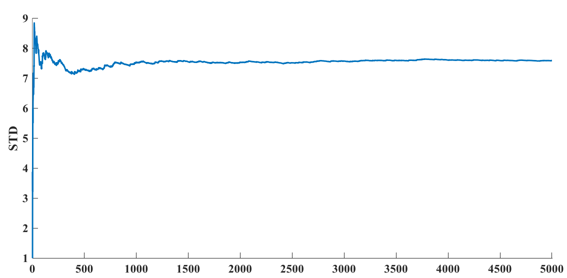

Fig. 3. The STD output for the first case

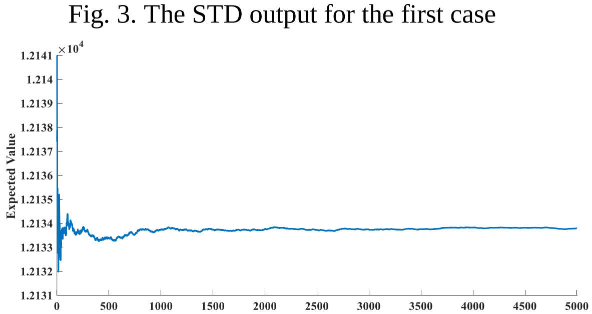

Fig. 4. The expected value output for the first case

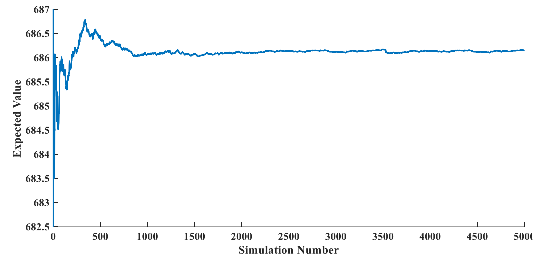

Fig. 5. The expected value output for the second case

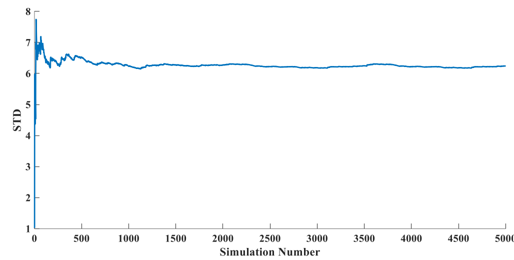

Fig. 6. The STD output for the second case

VII. CONCLUSION

The MAED problems as an extension of ED problems was studied in this paper. In this problem, a hierarchal process is used to supply demanded load in such a way that the information security in different areas is preserved. Moreover, the JAYA algorithm is utilized to find the optimal solution of MAED problem.

Despite all benefits of WTs, they have uncertainty challenges and to simulate this effect for real scenarios, the effect of WTs and uncertainty was also studied. The MCS as a well-known method was used to handle uncertainty in the MAED problems. To validate the proposed method via hierarchal process and MCS, two different dimensional cases were studied.

REFERENCES

[1] M. Basu, "Teaching–learning-based optimization algorithm for multi-area economic dispatch," *Energy,* vol. 68, pp. 21-28, 2014.

[2] A. L. Desell, E. C. McClelland, K. Tammar and P. r. V. Horne, "Transmission Constrained Production Cost Analysis in Power System Planning," in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 8, pp. 2192-2198, Aug. 1984.

[3] V. H. Quintana, R. Lopez, R. Romano and V. Valadez, "Constrained Economic Dispatch of Multi-Area Systems Using the Dantzig-Wolfe Decomposition Principle," in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, no. 4, pp. 2127-2137, April 1981.

[4] C. Wang and S. M. Shahidehpour, "A decomposition approach to nonlinear multi-area generation scheduling with tie-line constraints using expert systems," in *IEEE Transactions on Power Systems*, vol. 7, no. 4, pp. 1409-1418, Nov 1992.

[5] L. Wang and C. Singh, "Reserve-Constrained Multiarea Environmental/Economic Dispatch Using Enhanced Particle Swarm Optimization," *2006 IEEE Systems and Information Engineering Design Symposium*, Charlottesville, VA, 2006, pp. 96-100.

[6] J. Zhu, "Multiarea power systems economic power dispatch using a nonlinear optimization neural network approach," *Electric Power Components and Systems*, vol. 31, pp. 553-563, 2003.

[7] D. C. Secui, "The chaotic global best artificial bee colony algorithm for the multi-area economic/emission dispatch," *Energy*, vol. 93, pp. 2518-2545, 2015.

[8] P. Jorgensen, J. Christensen, and J. Tande, “Probabilistic load flow calculation using Monte Carlo techniques for distribution network with wind turbines,” in *Proc. 8th Conf. Harmonics Quality of Power*, Oct. 1998, vol. 2, no. 2, pp. 1146–1151.

[9] M. Aien, M. Fotuhi-Firuzabad and F. Aminifar, "Probabilistic Load Flow in Correlated Uncertain Environment Using Unscented Transformation," in *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2233-2241, Nov. 2012.

[10] M. Basil and A. Jamieson, “Uncertainty of complex systems by Monte Carlo simulation,” in *Proc. 16th North Sea Flow Measurement Workshop*, Gleneagles, U.K., Oct. 1998, pp. 1–10.

[11] R. Rao, "Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems," *International Journal of Industrial Engineering Computations*, vol. 7, pp. 19-34, 2016.