Multi Area Multi Objective Dynamic Economic Dispatch with Renewable Energy and Emissions

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Abstract: In this paper, multi area multi objective dynamic economic dispatch (MAMODED) with optimal real power dispatch in dynamic areas is considered. More accurate cubic cost function models thermal and emissions functions .The five-objective MAMODED includes thermal, renewable, tie line losses and emissions plus all the possible constraints. Uncertainties and variability of renewable energy (RE) sources are modelled using scenario based method (SBM). Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM) which is applied to validate the formulation resulted in better power exchange as compared to optimality condition decomposition (OCD) in terms of cost and emission reduction.

Keywords: Multi Area Multi Objective Dynamic Economic Dispatch (MAMODED), Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM), Renewable Energy (RE)

I: INTRODUCTION

Multi area multi objective dynamic economic dispatch (MAMODED) is an optimization scheme used to determine the best (optimal) generation schedule for a given load with minimum cost, while satisfying power balance of each dynamic area, and all the possible constraints. Thus, MAMODED problem with renewable energy (RE) is a large scale non-linear optimization problem with all technical constraints considered.

Motivation: The increased use of RE resources has been given a great deal of attention because of energy security, cost reduction and global environmental concerns. Further, increased penetration of RE mix into the electric power grid has revealed more planning and operational concerns. One of these concerns is the power wheeling problem in interconnected systems. A comprehensive approach is needed to model the MAMODED problem with all the aforementioned uncertainties in a real time system using a more realistic method that can handle stochastic variables.

According to [1], deterministic, heuristic and hybrid approaches have been considered for static multi area economic dispatch (MAED) formulated on quadratic cost functions. Deterministic method include Nonlinear Constrained Newton Flow Programming(NLCNFP)[2].Heuristic methods are Evolutionary Programming (EP) [3], Artificial Bee Colony (ABC)[4], Artificial Immune System (AIS) [5] and Secant Method(SM) [6]. In [7] Enhanced Particle Swarm Optimization (EPSO) is applied to the MAED with emissions, for the first time. Hybrid methods that have been used to handle the MAED are EP and Levenberg Marquardt Optimization (LMO) [EP-LMO] [8].This was later improved in [9] using Differential Evolution(DE),Particle Swarm Optimization (PSO), and PSO with time varying acceleration coefficients (TVAC) [PSO-TVAC] and fuzzy logic strategy (FLS) with evolutionary programming (EP) and Tabu-Search (TS) algorithms (EP-TS) [FLS- EP-TS] was applied.

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Other hybrids include evolutionary programming (EP) and dynamic programming (DP) [EP-DP] [10] and Genetic Algorithm (GA) and PSO [GA-PSO] [11].

In most of these works, static MAED with quadratic cost functions is considered. When a MAED problem is solved with reserve constraints, emissions, tie line loss, RE cost functions and all the practical constraints in place, the problem becomes further complicated. The power allocation to each unit is done in such a manner that after supplying the total load, some specified RE reserve is left for security reasons. In the event that the power in these areas is changing significantly, the classical methods of MAED solution are no longer applicable in such stochastic environments. Thus, more advanced hybrids must be applied to solved the MAMODED problem which has gained a lot of interest with the integration of renewable energy into the grid . For the first time cubic cost functions for the thermal and emission function are applied in a MAMODED environment.

II: MAED WITH RENEWABLE ENERGY

Two recent works have considered MAED with RE**.** In [12] a MAMODED for a retailer, a model taking into account hydrothermal, wind and a power reserve market is proposed. The uncertainties in wind power generations, energy prices and demand of the system are also modelled to make the proposed approach more practical in case of real-time operation of practical power systems. Scenario-based method (SBM) is adopted for uncertainty modeling and optimality condition decomposition (OCD) technique is employed along with parallel computation to solve the problem. In [13], a penalty function-hybrid direct search method (PF-HDSM) is also developed for the solution of multi-area wind-thermal coordination dispatch problem. In these two works however, only wind is considered and quadratic cost functions are used. Further all the practical constraints have not been considered.

Contributions: More accurate cubic cost functions have been used in the wheeling mechanism, for the first time, to model the thermal and emission leading to more realistic costs and emissions. Five-objective MOMADED has been proposed considering thermal, wind, solar, emission and tie line losses objective functions. In addition to the static constraints, RE constraints with stochastic variables have been considered. Uncertainties in RE have been incorporated in the problem formulation using scenario based method (SBM) in [15] and the problem solved using the Modified Firefly Algorithm with Levy Flights and Derived Mutation **(**MFA-LF-DM).

III: PROBLEM FORMULATION

A: Problem Formulation

*Thermal Cost Function***:** Multi area single objective DED (MASODED) with a cubic objective function is defined by the relation

$$F(P_{i,m}) = \min \sum_{m=1}^{M} \sum_{i=1}^{T} \big(a_{i,m} P_{i,m}^3 + b_{i,m} P_{i,m}^2 + c_{i,m} P_{i,m} + d_{i,m} + r_{i,m} + \left|e_{i,m} \sin f_{i,m} (P_{i,m}^{min} - P_{i,m})\right|\big) \quad (1)$$

where $P_{i,m}$ is the power output of generator i in area m, $a_{i,m,} b_{i,m,}$ *and* $c_{i,m,}$ are the fuel cost coefficients of the i^{th} unit in area m ,M is the number of areas and T is the number of online thermal units for the area M .

Wind Cost Function: The operational cost objective function for wind power generation in a multi area scenario for the i^{th} wind generator in the j^{th} hour in area m is defined as

$$F(w_{ijm}) = \min \sum_{m=1}^{M} \sum_{j=1}^{H_W} \sum_{i=1}^{W} \begin{bmatrix} F_{wi}(w_{ijm}) + \\ F_{p,wi}(w_{ijm,av} - w_{ijm}) \\ +F_{r,wi}(w_{ijm} - w_{ijm,av}) \end{bmatrix} \quad (2)$$

where H_W is the total number of hours the wind generator is in operation and W is the the total number of wind generators in the system. In this case, w_{ijm} is the scheduled output of the i^{th} wind generator in the j^{th} hour in area m. $F_{wi}(w_{ijm})$ is the weighted cost function representing the cost based on wind speed profile, $F_{p,wi}(w_{ijm,av} - w_{ijm})$ is the penalty cost for not using all the available wind power and $F_{r,wi}(w_{ijm} - w_{ijm,av})$ is the penalty reserve requirement cost which is due to the fact that that available power is less than the scheduled .

Solar Cost Function: The operational cost objective function for the PV power generation in a multi area scenario for the i^{th} solar generation plant in the j^{th} hour in area m is defined as

$$F(PV_{ijm}) = \min \sum_{m=1}^{M} \sum_{j=1}^{H_S} \sum_{i=1}^{S} \begin{bmatrix} F(PV_{ijm}) + F_{p,PVi}(PV_{ijm,av} - PV_{ijm}) \\ +F_{r,PVi}(PV_{ijm} - PV_{ijm,av}) \end{bmatrix} \quad (3)$$

where H_S is the total number of hours the wind generator is in operation and S is the the total number of solar generation plants in the system. $F_{PVi}(PV_{ijm})$ is the weighted cost function representing cost based on solar irradiance profile $F_{p,PVi}(PV_{ijm,av} - PV_{ijm})$ is the penalty cost for not using all the available solar power, and $F_{r,PVi}(PV_{ijm} - PV_{ijm,av})$ is the penalty reserve requirement cost due to the fact that the available power is less than the scheduled.

Tie line losses cost function: The transmission cost in MADED for power transfer between areas can be expressed as

$$F(T) = \sum_{m=1}^{M-1} \sum_{k=m+1}^{M} f_{mk} T_{mk} \quad (4)$$

where T_{mk} is the tie line from area m to k , f_{mk} is the transmission cost coefficient relevant to T_{mk} and T is the vector of real power transmission between areas defined as

$$T = T_{1,2}, \ldots, T_{1,M}, T_{2,3} \ldots, T_{2,M} \ldots, T_{M-1,M} \quad (5)$$

In this case the power exchange between any two interconnected areas m and k are equal but opposite .This can be represented as

$$T_{mk} = -T_{km} \quad (6)$$

Emissions Cost function: Minimization of pollutant emissions in a MADED with m areas can be approximated by the cubic cost function for the y^{th} generator output

$$F(E) = \sum_{m=1}^{M} \sum_{y=1}^{Y} (\beta_{3,ym} P_{t,ym}^3 + \beta_{2,ym} P_{t,ym}^2 + \beta_{1,ym} P_{t,ym} + \beta_{0,ym} + \zeta_{3,ym} \exp(\lambda_{3,ym} P_{ym}) + \zeta_{2,ym}) \quad (7)$$

where $Y = T + W + S$, the total number of thermal, wind and solar generators. β, ζ and λ are the respective coefficients of the generator emission characteristics. The three main emissions that are considered are NO_X , SO_2 and CO_2 for the power plants in the MAMODED system.

Using (1), (2), (3), (4) and (7) overall operational cost for MAMODED with thermal and renewable units, tie line losses and emissions can be formulated as

$$F = h[F(P_{i,m}) + F(w_{ijm}) + F(PV_{ijm}) + F(T)] + (1-h)F(E) \quad (8)$$

Where h is the weighting factor

B: Constraints

- Import export area power balance constraint(IEAPBC)

$$\sum_{m=1}^{M} \sum_{y=1}^{Y} P_{i,m} - \sum_{m=1}^{M} \sum_{i=1}^{N_d} P_{Da,im} - \sum_{k,k\neq m} T_{mk} = 0 \quad m = 1,2, \ldots M \quad (9)$$

where N_d the number of loads in area m, T_{mk} is the total tie line real power loss in a multiarea system, $P_{Da,im}$ is the active actual load at node i in the area m

- Area Spinning Reserve Constraint (ASRC):In area m, the spinning reserve requirement should be satisfied multi area reserve sharing by the relation

$$\sum_{y=1}^{Y} S_{i,m} \geq S_{req,m} + \sum_{k,k\neq m} R_{mk} \quad m = 1,2,3 \ldots M \quad (10)$$

where $S_{i,m}$ is the spinning reserve of unit i in area m equals to $S_{i,m} = P_{i,m}^{max} - P_{i,m}$, $S_{req,m}$ is the required spinning reserve in area m and R_{mk} is the reserve contribution from area m to area k.A new vector R is defined to represent the reserve sharing between areas as

$$R = [R_{1,2}, \ldots, R_{1,M}, R_{2,3}, \ldots, R_{2,M}, \ldots, R_{M-1,M}] \quad (11)$$

- Transmission Capacity Limits (TCL):The transfer including both generation and reserve from area m to k should not exceed the tie line transfer capacities for security considerations .This can be expressed as

$$T_{mk,min} \leq T_{mk} + R_{mk} \leq T_{mk,max} \quad (12)$$

where $T_{mk,min}$ and $T_{mk,max}$ represents the tie line transmission capability

- Tie Line Flow Constraint(TLFC)

$$|P_t| \leq P_{t,max} \; t = 1,2,3 \ldots \ldots . . N_t \quad (13)$$

where N_t the number of is tie lines and P_t is the active power flow in the tie line t

- Thermal unit generation limits (TUGC)

$$P_{im,min} \leq P_{im} \leq P_{im,max} \quad (14)$$

where $P_{im,min}$ and $P_{im,max}$ are the minimum and maximum power outputs of the i^{th} thermal unit in area m.

- Ramp up and ramp down constraint (RURDC):The variation of the output power in the thermal generating units is limited in the transition time from $t-1$ to t .This limitation is called ramp rate and is stated as

$$P_{im}(t-1) - DR_{im} \leq P_{im} \leq P_{im}(t-1) + UR_{im} \quad (15)$$

where DR_{im} and UR_{im} are the ramp down and ramp up limits of the i^{th} thermal unit (MW/h) in area m

- Net Actual Demand Constraint (NADC):The net actual demand is expressed as;

$$\sum_{m=1}^{M} \sum_{i=1}^{N_d} P_{Da,im} = \sum_{m=1}^{M} \sum_{i=1}^{N_d} P_{Dt,im} - \sum_{m=1}^{M} \sum_{j=1}^{H_w} \sum_{i=1}^{W} w_{ijm,av} -$$

$$\sum_{m=1}^{M}\sum_{j=1}^{H_S}\sum_{i=1}^{S} PV_{ijm,av} \pm P_R \quad (16)$$

where, $PV_{ijm,av}$ and $w_{ijm,av}$ are solar and wind power generated respectively. P_R is the renewable reserve power where the positive sign is applicable during the storage whereas the negative sign is used during the delivery periods.

- Dispatched RE constraint (DREC):The dispatched amount of renewable power is limited to some part (x) of the total actual RE demand, that is

$$(PV_{ijm} + w_{ijm})_d \leq xP_{Da,im} \quad (17)$$

- Reserved Power Constraint RPC)

$$P_R \leq \left(PV_{ijm,av} + w_{ijm,av}\right)_g - \left(PV_{ijm} + w_{ijm}\right)_d, \text{during} T_a \quad (18)$$

$$P_R \leq y\sum_{T_a}\left(PV_{ijm,av} + w_{ijm,av}\right)_g - \left(PV_{ijm} + w_{ijm}\right)_d, \text{during} T_u \quad (19)$$

Where $y \propto \frac{T_a}{T_u} P_D^a$ in such a way that

$$\sum_{T_u} P_R \leq \sum_{T_a} P_R \quad (20)$$

The aim of introducing solar energy is to extract maximum amount of power from solar reactor during its available period (T_a). solar power generated during this period is stored in available storage devices called renewable reserve. This stored power is delivered during unavailable period (T_u) of sun light. The power extracted from the renewable source varies and can be considered as a variable load. Therefore this power $(PV_{ijm,av} + w_{ijm,av})$ is deducted from the total demand P_{Dt} and also the reserve power (P_R) is added to it (duringT_a) or subtracted from it (during T_u)to obtain the actual demand P_{Da}which is distributed among the available generating units. The reserved power is the difference of the total extracted and dispatched amount of renewable power during Ta. During $T_u$it must not exceed some part (y) of the total stored renewable power of T_a period. Moreover, the sum of total power delivered from the storage devices during T_u must not exceed the total power stored during T_a[14].

IV: PROPOSED METHODOLOGY

Many heuristic methods have been used in the recent past to handle the static MAED. In this paper, MFA-LF-DM is proposed as it outperforms the more popular Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Artificial Bee Colony (ABC) since it converges more quickly ,deals with global optimization more naturally, more efficient and has higher success rates. The method can handle NP Hard Problems and further, it is well fitted for the intermittent search strategy [15].

In this section, we consider the uncertainty and variability modelling of the RE sources using Scenario-based method (SBM) and the modified firefly algorithm with levy flights and derived mutation (MFA-LF-DM) which is applied to solve the MAMODED problem.

A: Scenario-Based Method (SBM)

For a multivariate function,$y = F(X)$ where X is a vector containing the uncertain input values, the SBM uncertainty modelling is a method for finding the expected value of y. A set of scenarios, $\Omega_s$is generated for describing the probable values of X such that [15, 23];

$$y = \sum_{s\epsilon\Omega_s} \pi_s F(X_s) \quad (21)$$

where π_s is the probability of state s.

Uncertainties and variability in RE power generation, reserve market prices and load profile of the system, emerge into a probabilistic MAMODED which is formulated in this paper. The total cost of energy procurement is given by

$$C_T = \sum_{S,t,m} \pi_s PP_{s,m}(t)\lambda_s(t) + \sum_{i,t,m} C_{im}\left(P_{im}(t)\right) \quad (22)$$

where C_T is the total cost paid by the retailer, π_s is the probability of scenario s, $PP_{s,m}(t)$ is the purchased power from reserve market in time t ,scenario s and area m, $\lambda_s(t)$ is the price of energy purchased from the power reserve in time t ,scenario s($/MWh) and $C_{im}(P_{im}(t))$ is the production cost of the i^{th} thermal unit located in area m in time t.The objective function of a rational retailer that is to be maximized is defined by

$$F = \sum_{S,t,m} \pi_s P_{D,s,m}(t)\lambda_c(t) - C_T \quad (23)$$

where $\lambda_c(t)$the price of energy is sold to customers in time t, and $P_{D,s,m}(t)$ is the load demand at time, scenario s and area m.

B: Modified Firefly with Levy Flights and Derived Mutation (MFA-LF-DM)

a) Firefly Algorithm (FA)

Fireflies are the most charismatic species among the insects and their spectacular display have inspired engineers and scientists. They produce short rhythmic patterns of flashing lights which are unique, varying from species to species, and the flashing light is produced by a *bioluminescence* process. The flashing behavior of fireflies plays a key role in reproduction, protection, communication and feeding [16-17].

Firefly Algorithm (FA) is a new nature inspired algorithm developed by Xin-She Yang in the year 2007, based on the flashing behavior of fireflies. The flashing signifies the signal to attract other fireflies, where the *objective function* is associated with the flashing light or the light intensity which helps the fireflies to move to brighter and more attractive locations to achieve optimal solution. FA has three idealized rules which have been developed to define the characteristics of fireflies [16]: These include the law of attraction, the law of separation, and the law of objective function [16].

Relatively, FA has become popular and successful because the method [17]: i) Automatically divides its population into subgroups, because of the fact that local attraction is stronger than long distance (global) attraction. ii) Does not use historical individual best and explicit global best. This reduces the potential drawbacks of premature convergence. iii) Does not use the velocities hence problems associated with velocities in PSO is automatically eliminated. iv) Has an inbuilt ability to modify and therefore to control the parameters such as γ, leading to improved results. Hence FA is more efficient in respects of controlling parameters, local search ability, robustness and elimination of premature convergence.

However the basic FA is poor in global searching and optimization, long convergence time, requires more iterations, and low computational speed. These problems can be addressed by using modified FA [18] and using heuristic and deterministic methods to form hybrid FA [19]. In a hybrid method the weaknesses of the base method are suppressed while its strengths are exalted leading to better realistic results and improved performance of the method .In this paper therefore, an hybrid of Modified FA (MFA) with Levy-Flights (LF)[MFA-LF] coupled with Derived Mutation (DM);[MFA-LF-DM] is proposed.

b) Characteristics of MFA-LF-DM

There are six characteristics of the proposed MFA-LF-DM. These include brightness, distance, attractiveness, movement, randomness reduction and mutation. The first three are as in [16].This paper considers the later three.

Movement: The movement of a firefly i is attracted to another more attractive (brighter) firefly j by the relation

$$x'_{i+1} = x_i + \beta_0\, r\, e^{-\gamma r^2} + \alpha \text{ sign}\left[rand - \frac{1}{2}\right] \qquad (24)$$

where x_i is the current position of a firefly, the second term defines the fireflies attractiveness to light intensity as seen by the adjacent firefly and the third term is for the random movement of a firefly if no brighter firefly is left, α is a randomization parameter, rand is a random number generator uniformly distributed over the space [0, 1], that is, $rand \in [0,1]$.In general the solutions can be improved by reducing the randomness by

$$\alpha = \alpha_\infty + (\alpha_0 - \alpha_\infty)e^{-t} \qquad (25)$$

where $t \in [0, t_{max}]$ is the pseudo time for simulation and t_{max} is the maximum number of generations, α_∞ and α_0 are the final and initial values of the randomness parameter

Randomness Reduction: Levy flight is a random walk of step lengths having direction of the steps as isotropic and random. The concept propounded by Paul Pierre Levy (1886-1971) is very useful in stochastic measurements and simulations of random and pseudo-random phenomena

The movement of a firefly i with Levy Flights is defined by the relation

$$x'_{i+1} = x_i + \beta_0\, r\, e^{-\gamma r^2} + \alpha \text{ sign}\left[rand - \frac{1}{2}\right] \oplus \text{Levy} \qquad (26)$$

where the second term is due to attraction, while the third term is randomization via the Levy Flights with α being the randomization parameter.The product ⊕ means entry wise multiplication. The $\text{sign}\left[rand - \frac{1}{2}\right]$ where $rand \in [0,1]$ essentially provides a random sign or direction while the random step length is drawn from a Levy distribution with infinite variance and infinite mean given by

$$Levy \sim u = t^{-\lambda}, (1 < \lambda \leq 3) \qquad (27)$$

where λ is the levy distribution parameter.

Mutation: To further improve the exploration of or diversity of the candidate solution, the simple mutation corresponding to α from the Ant Colony Optimization (ACO), Genetic Algorithm (GA) and Evolutionary Programming (EP) and Differential Evolution (DE) is adopted in the MFA-LF process. This enhances the optimum results in solving the fully-constrained SODED problem. In this method the initial solution is generated randomly within the feasible range, the MFA-LF parameters used in the MAMODED problem are as shown in table 1.0

TABLE 1.0 PARAMETERS FOR MFA-LF-DM

Parameter	Value
Brightness	$F(x)$
Alpha (α)	0.9
Beta (β)	0.5
Gamma (γ)	1.0
Number of fireflies (n)	50
Maximum no. of iterations	100
Attraction at $r = 0$, (β_0)	2.5
Lambda (λ)	1.5

V: RESULTS DISCUSSION AND ANALYSIS

There are six thermal sources in each area whose cubic cost coefficients and emission coefficients (for SO_2, NO_X and CO_2) are as in [20] .The necessary wind and solar power parameters are as in [21]. Solar power dominates variability and wind power dominates uncertainty. The renewable power that is available at different scenarios of the study are as shown in table 2.0 and the area generation capacity for wind and solar 300MW and 250MW respectively. The test case consists of five interconnected areas. The one line diagram of the 5-area MAMODED is as shown in [12] except that the power sources in each areas are as shown in Table 3.0. The area m_1 is a central area with a thermal source and a RE reserve ,it is connected to the other four areas through tie lines The tie-lines' flow limits are as shown in Table 4.0 .

TABLE 2.0: RENEWABLE POWER IN VARIOUS STATES

States Ω_s	$w_{ij,s}$ %, $PV_{ij,s}$ %	$\pi_{s,w}$	$\pi_{s,s}$
1	0	0.2043	0.3082
2	5	0.0810	0.0019
3	15	0.1322	0.1585
4	20	0.3026	0.7965
5	35	0.3121	0.5824
6	45	0.0803	0.1912
7	55	0.0878	0.0078
8	65	0.0609	0.2109
9	75	0.0356	0.1663
10	85	0.0217	0.0006
11	95	0.0142	0.0315
12	100	0.0665	0.4279

TABLE 3.0: POWER SOURCES IN THE AREAS

Area	Objectives	% RE
m_1	Thermal(T),Reserve(R)	16
m_2	Thermal(T), Wind(W)	33
m_3	Thermal(T), Solar(S)	33
m_4	Thermal(T), Wind(W), Solar(S)	67
m_5	Thermal(T)	0
Overall Penetration		30

TABLE 4.0: TIE LINE FLOW LIMITS

Tie Line	Power(MW)
T_{1-3}	250
T_{1-4}	200
T_{1-5}	250
T_{2-3}	200
T_{3-5}	250
T_{2-4}	250

A: Power cost in 5-Area MAMODED

The hourly expected demand in each area is as shown in table 5.0 while the hourly power cost in scenarios $1 \rightarrow 5$ are as shown in table 6.0. This trend repeated in the upcoming scenarios $6 \rightarrow 15$. For the RE mix, $H = H_W = H_S$. In this paper, the retailer is paid a fixed price for each MWh, which he sells to the customers. There are three options for supplying the demand of its customers namely; thermal generating units, wind power generation and finally solar power systems. The tie line losses and the emissions are accounted for after the REs have been accounted for. The hourly change in demand in the five areas and the hourly variation in power cost due to RE penetration can be explained using the *cycling principle* of thermal generators and the *free nature* of renewable sources [22]. *Cycling* includes both *starting* and *ramping*. Starting is defined as starting a unit that is offline while ramping is defined as a load-following operation in which a generating unit increases its production. Adding wind and solar affects the operation of the thermal plants and high RE penetrations induces cycling of such fossil-fueled generators. Frequent cycling of thermal plants creates thermal and pressure stresses in the plant components leading to increased operation and maintenance costs, more frequent repairs, reduced component life, and more frequent forced outages. Power plants that were designed for base loaded operation suffer much more wear-and-tear damage from cycling. Over time, these can result in premature component failure and increased maintenance and repair. Utilities are concerned that cycling effects can significantly negate the benefits that RE bring to the system. And to plan accordingly, power plant owners need to understand the magnitude of cycling impacts.

For average fossil-fueled plant considered in this case, 30% RE in MAMODED penetration causes cycling costs to increase by $\$0.47–\$1.28/MWh$ compared to total fuel and variable operations and maintenance costs of $\$27–\$28/MWh$ which is displaced by using renewable resources which are free in nature. This is how RE penetration leads to reduced wheeling costs and the variable demand in interconnected systems.

TABLE 5.0: HOURLY EXPECTED DEMAND (MW)

Hour (H)	m_1	m_2	m_3	m_4	m_5
t_1	855.2	712.5	698.4	527.0	548.5
t_2	994.4	754.0	808.2	621.0	685.0
t_3	1168.8	1035.5	1190.4	984.0	1028.0
t_4	1064.0	791.5	822.6	608.5	607.5
t_5	924.8	853.5	978.0	662.0	633.5
t_6	1099.2	930.5	998.4	754.5	757.0
t_7	1307.2	1125.5	1157.4	806.0	890.5
t_8	1412.0	1182.5	1231.8	1022.0	976.0
t_9	1516.0	1191.0	1147.8	906.5	796.5
t_{10}	1446.4	1112.5	1284.0	914.0	883.0
t_{11}	1272.8	1030.5	1133.4	806.5	821.0
t_{12}	1233.6	839.0	899.4	655.0	658.5
t_{13}	1099.2	924.5	1083.0	726.5	761.5
t_{14}	994.4	748.5	896.4	649.0	748.5
t_{15}	890.4	861.0	952.8	743.0	753.0
t_{16}	820.8	789.0	945.0	648.5	709.0
t_{17}	716.8	657.0	754.2	580.0	660.0
t_{18}	890.4	761.0	819.6	660.0	628.5
t_{19}	994.4	887.5	882.0	623.0	598.5
t_{20}	1133.6	889.0	985.2	658.0	701.5
t_{21}	1307.2	1106.5	1150.2	815.5	803.5
t_{22}	1381.6	1098.5	1167.0	968.5	1068.5
t_{23}	1272.8	972.0	945.0	749.0	803.0
t_{24}	994.4	934.0	1046.4	797.0	765.5

B: Emissions in 5-Area MAMODED

For the three major emission case, the hourly emissions in ton/h are as shown in table 7.0. The emissions are the highest in area m_5 since all the major emissions are maximally available in the pure thermal base case. With wind penetration in area m_2, there are less emissions as compared to m_5. This is because wind generators reduce emissions by forcing the most polluting and inflexible thermal power plants offline and causing them to be replaced by more efficient and flexible types of generation especially the RE systems. Obtaining 6% of electric power from wind energy would reduce emissions CO_2-4.5%,SO_2-6.0% and NO_X-6.0% [21-22] .Coal and natural gas consumption reduced by 3% and 14% respectively**.** More efficient systems mean reduced losses and reduced cost. With penetration of solar in m_3 there is reduced emission but these emissions are slightly higher as compared to high wind penetration in m_2 . While there are no global warming emissions associated with solar power generation directly, there are emissions associated with other stages of the solar PV life-cycle, including manufacturing, materials transportation, installation, maintenance, and decommissioning and dismantlement. Most estimates for concentrating solar power range from $0.04 - 0.10\ kg\ CO_2/KWh$.. In both cases, this is far less than the lifecycle emission rates for natural gas $0.30 - 1.0\ kg\ CO_2/KWh$.and coal $0.7 - 1.8\ kg\ CO_2/KWh$[14]. The main components of solar PV panels are made from crystalline silicon. Manufacturing these components is an energy-intensive process which accounts for 60% of the total energy used to make solar panels. However the NO_x and SO_2 emissions remain almost the same as in wind power penetration.

TABLE 6.0: POWER COST IN SCENARIOS $1 \rightarrow 5$ ($/MWh)

Hour (H)	s_1	s_2	s_3	s_4	s_5
t_1	29.09	58.80	64.52	39.75	48.59
t_2	19.60	54.40	52.82	51.37	16.66
t_3	17.58	32.90	49.44	38.50	26.89
t_4	50.30	18.10	10.02	17.33	23.64
t_5	35.03	67.54	40.65	18.92	25.40
t_6	42.51	47.14	97.25	50.23	26.92
t_7	39.47	36.82	26.06	16.51	47.48
t_8	46.36	05.10	63.59	18.56	45.36
t_9	23.41	31.44	23.06	18.31	47.49
t_{10}	20.06	61.82	42.67	20.68	40.14
t_{11}	19.39	32.55	18.98	20.17	37.98
t_{12}	18.55	80.02	29.68	25.19	40.78
t_{13}	25.17	70.48	58.03	17.70	57.91
t_{14}	16.74	35.24	37.22	20.53	50.05
t_{15}	37.00	07.29	20.51	19.50	52.14
t_{16}	50.79	50.65	80.79	21.41	56.94
t_{17}	42.74	35.62	23.25	28.70	54.93
t_{18}	50.28	54.51	31.28	38.69	58.23
t_{19}	35.89	63.01	69.40	47.44	40.14
t_{20}	39.91	51.98	53.79	20.06	39.54
t_{21}	20.03	20.92	58.02	38.74	30.36
t_{22}	19.59	39.50	48.33	17.78	36.36
t_{23}	38.65	62.37	30.41	20.18	29.03
t_{24}	44.08	73.56	19.94	36.72	19.44

TABLE 7.0: HOURLY EMISSIONS (ton/h)

Hour (H)	m_1	m_2	m_3	m_4	m_5
t_1	6.49	6.15	6.32	6.24	6.52
t_2	5.42	5.05	5.22	5.15	5.45
t_3	8.05	7.58	7.75	7.68	8.08
t_4	7.49	7.13	7.30	7.22	7.52
t_5	3.53	3.11	3.28	3.20	3.56
t_6	7.08	6.63	6.80	6.78	7.00
t_7	1.24	0.92	1.09	1.05	1.25
t_8	6.06	5.65	5.82	6.76	6.09
t_9	6.51	6.18	6.35	6.23	6.53
t_{10}	3.09	2.61	2.78	2.72	3.09
t_{11}	1.32	0.93	1.10	1.05	1.35
t_{12}	8.51	8.14	8.31	8.19	8.54
t_{13}	1.54	1.17	1.33	1.26	1.56
t_{14}	8.52	8.23	8.40	8.38	8.56
t_{15}	3.03	2.53	2.70	3.65	3.05
t_{16}	9.03	8.68	8.85	8.80	9.06
t_{17}	1.82	1.45	1.62	1.55	1.85
t_{18}	8.52	8.17	8.34	8.29	8.56
t_{19}	5.54	5.14	5.31	5.25	5.58
t_{20}	1.50	1.17	1.34	1.26	1.52
t_{21}	3.53	3.18	3.33	3.26	3.56
t_{22}	8.55	8.15	8.32	8.28	8.58
t_{23}	3.22	2.58	2.75	2.68	3.08
t_{24}	6.45	6.18	6.35	6.29	6.59

The lowest emissions are in m_4 due to the RE mix. Cycling of thermal power plant due to RE mix penetration results in change of emissions. Starting a generator or increasing its output can increase emissions compared to noncyclic operation. Also, operating a generator at part-load also affects emissions rates. Up to 33% RE avoids 29– 34% CO_2, 16–22% NO_x and 14– 24% SO_2. Cycling had very little ($< 5\%$) impact on the CO_2, NO_x, and SO_2 emissions reductions from wind and solar. For the average fossil-fueled plant, RE-induced cycling can have a positive or negative impact on CO_2, NO_x, and SO_2 emissions rates, depending on the RE mix and penetrations. Average overall emissions in the interconnected system is lower compared to the purely thermal system since the CO_2, NO_x, and SO_2 emissions reduce greater significantly as compared to the cycling emissions.

D: Comparison of MFA-LF-DM and OCD

The proposed MFA-LF-DM was compared with Optimality Condition Decomposition (OCD) in [12] and the results tabulated in Table 8.0. It should be noted that in [12] the thermal units are modelled using quadratic cost functions and only wind as a RE resource is considered. Emissions effects have not been considered. For feasible comparison, these gaps were addressed in this work using OCD. From the tabulated results, the proposed method results in better emissions and reduced cost in the MAMODED problem for equal number of iterations. Fewer scenarios and iterations are required to simulate a real-time application.

TABLE 8.0: COMPARISON OF MFA-LF-DM WITH OCD

Iteration	Optimal Benefit ($)		Emissions (ton/MWh)	
	MFA-LF-DM	OCD [15]	MFA-LF-DM	OCD[15]
1	2322.48	2303.01	480.78	475.76
2	1955.08	1942.45	81.80	80.50
3	1997.32	1987.11	318.01	315.90
4	2147.01	2140.89	10.00	09.50
5	2182.98	2176.50	981.13	979.86
6	2140.49	2123.66	290.17	285.67
7	2112.37	2101.90	367.20	366.12
8	2118.47	2115.34	464.03	460.65
9	2130.84	2115.60	834.24	820.87
10	2132.85	2128.45	847.93	840.85
11	2128.99	2108.23	990.09	985.87

VI: CONCLUSION

In this paper, MAMODED problem is formulated for a hybrid system which includes thermal generating units, solar, wind and renewable reserve with all the possible technical constraints. More accurate cubic cost functions for the thermal and emissions have been used for the first time in MAMODED formulation. The MFA-LF-DM hybrid has been used to validate the proposed formulation and OCD been used to do a comparison .The uncertainties of RE have been modelled using the scenario-based method (SBM). Analysis was carried out using MATLAB simulation for a high solar irradiation region using a five-area MAMODED. MAMODED with RE is the more efficient and realistic way to fulfill future demand with reduced cost and emissions in interconnected systems.

REFERENCES

[1] Jizhong Zhu (2009) *Optimization of Power System Operation,* New Jersey &Canada: John Wiley and Sons

[2] Streiffert, D., "Multi-area economic dispatch with tie line constraints," *Power Systems, IEEE Transactions on*, Vol.10, No.4, pp.1946, 1951, Nov. 1995.

[3] T. Jayabarathi, G. Sadasivam and V. Ramachandran , "Evolutionary Programming-Based Multiarea Economic Dispatch with Tie Line Constraints", *Electric Machines & Power Systems*, pp. 1165-1176,2000

[4] M.Basu "Artificial bee colony optimization for multi-area economic dispatch "International Vol. 49, July 2013, pp. 181–187, 2013.

[5] De,Shankha Suvr et al "Artificial Immune System for Multi-Area Economic Dispatch" *International Journal of Emerging Electric Power Systems* Vol. 14, Issue 6, pp.581-590, Dec 2013.

[6] Sudhakar A.V.V et al "Multi Area Economic Dispatch using Secant Method" *Journal of Electrical Engineering Technology* Vol. 8, No. 4: 744-751,2013.

[7] Vinay Kumar et al "Multi-Area Environmental Economic Dispatch with Reserve Constraints using Enhanced Particle Swarm Optimization" *Electric Power Components and Systems*, Vol; 43 ,Issue 14,pp 1667-1679,August 2015.

[8] Prasanna.T.S and Somasundaram. P "Multi-Area Security Constrained Economic Dispatch by Fuzzy- Stochastic Algorithms" *Journal of Theoretical and Applied Information Technology,* pp 88-94, 2009.

[9] Manisha Sharma et al "Reserve Constrained Multi-Area Economic Dispatch Employing Evolutionary Approach *"International Journal of Applied Evolutionary Computation* Vol .1 Issue 3 pp. 49-69 July 2010.

[10] S.Chitra Selvi et al "Hybrid Evolutionary Programming Approach to Multi-Area Unit Commitment with Import and Export Constraints" *International Journal of Recent Trends in Engineering*, Vol.1,No. 3, 223-228, May 2009.

[11] Huynh This and Thanh Binh "Hybrid Particle Swarm Optimization for Solving Multi-Area Economic Dispatch Problem" *International Journal on Soft Computing (IJSC*) Vol.4, No.2, pp. 17-27 May 2013.

[12] Soroudi, A.; Rabiee, A "Optimal multi-area generation schedule considering renewable resources mix: a real-time approach," in *Generation, Transmission & Distribution, IET*, vol.7, no.9, pp.1011-1026, Sept. 2013.

[13] Chun-Lung Chen, Zih-Yan Chen, Tsung-Ying Lee "Multi-area economic generation and reserve dispatch considering large-scale integration of wind power" *International Journal of Electrical Power & Energy Systems*, Volume 55, Pages 171-178,February 2014.

[14] F. R. Pazheri, M. F. Othman, N. H. Malik, and Safoora O. K "Economic and Environmental Dispatch at Highly Potential Renewable Area with Renewable Storage" *International Journal of Environmental Science and Development, Vol. 3, No. 2, pp.177-182 , April 2012*

[15] Yang X.S., "Firefly Algorithm: Recent Advancements And Applications", *International Journal of Swarm Intelligence*, vol. , pp. 36-50, 2013.

[16] Yang X.S., "Firefly algorithm, stochastic test functions and design optimization",*International Journal Of Bio-Inspired Computation*, vol. 2, issue 2, pp. 78-84, 2010.

[17] Fister I., Iztok Fister I. Jr., Yang X. S., Brest J., "A comprehensive Review of Firefly Algorithms", *Swarm And Evolutionary Computation*, vol. 13, pp. 34-46, 2013.

[18] X.-S. Yang,"Firefly algorithm, L´evy flights and global optimization", in: *Research and Development in Intelligent Systems* XXVI (Eds M. Bramer, R. Ellis, M. Petridis), Springer London, pp. 209-218 ,2010.

[19] Younes M., "A Novel Hybrid FFA-ACO Algorithm for Economic Power Dispatch", *Journal of Control Engineering And Applied Informatics*, Vol. 15, Issue 2, Pp. 67-77, 2013.

[20] Krishnamurthy, S.; Tzoneva, R., "Impact of price penalty factors on the solution of the combined economic emission dispatch problem using cubic criterion functions," *Power and Energy Society General Meeting, 2012 IEEE* , vol., no., pp.1,9, 22-26 July 2012

[21] IPCC, 2011: Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change,Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1075 pp. (Chapter 7 & 9).

[22] Debra Lew and Greg Brinkman "The Western wind and solar integration study phase 2: Executive Summary"National Renewable Energy Laboratory, Technical Report NREL/TP-5500-58798,Sept 2013.