Multi Area Multi Objective Dynamic Economic Dispatch with Renewable Energy and Multi Terminal DC Tie Lines

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***Abstract*: In this paper, an improved wheeling method (IWM) for a fully constrained five –area multi area multi objective dynamic economic dispatch (MAMODED) with renewable energy(RE) is proposed where the area interconnections is achieved using multi terminal DC(MTDC) tie lines for the first time. A three-method hybrid of Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM) is used to illustrate the optimization of the system. The levy flights reduce the random movement of the objective function while the derived mutations are improve the exploration of the candidate solution. The uncertainties and variability of the renewable sources are modelled using scenario based method (SBM). A comparison will be made using the MAMODED with RE but traditional HVAC interconnections. The simulation results reveal that integration of RE led to an IWM with reduced cost and emissions.Further use of MTDC interconnection gave better optimal results as compared to the traditional HVAC tie lines.**

Index Terms: HVAC, Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM), MTDC, Multi Area Multi Objective Dynamic Economic Dispatch (MAMODED)

I: INTRODUCTION

Three recent works have considered multi area economic dispatch (MAED) with renewable energy (RE). In [1], 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 for 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. The proposed approach demonstrates the real-time scheduling of joint thermal systems with undispatchable wind energy in a three-area and five-area multi area system. In [2], a penalty function-hybrid direct search method (PF-HDSM) is also developed for the solution of multi-area wind-thermal coordination dispatch problem. In [8], security and control areas of MAMODED with wind and solar REs were addressed. In these work however, only wind is considered and quadratic cost functions are used. Further, HVAC tie lines have been used for area interconnections .In this paper, five-objective MAMODED with thermal, wind, solar, emissions and MTDC tie line objectives functions is proposed and all the possible constraints considered.

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With the integration of RE into the areas, grids and procedures have to be adopted for rapid variations renewable power production. Although the present HVAC grids will remain the backbone of transmission systems, area tie lines must be able to cope with the operational properties of renewable generation as well as being compatible with the existing HVAC links. The links between the areas must allow rapid, efficient and reliable control of power flows, grid voltages and back up generation [4]. HVDC links are proposed because of their asynchronous operation, power control and stability and the ability to operate at different frequencies.

The rest of the paper is organized as follows: Section II deals with HVAC and HVDC interconnections, Section III is the problem formulation, Section IV is the proposed methodology, Section VI are the results and section VII forms the conclusion of the paper.

II: HVAC AND HVDC INTERCONNECTION

When two dynamic areas are to be interconnected by an HVAC tie line, it is necessary that there should be sufficiently close frequency control on each of the areas. Such an interconnection is called *synchronous interconnection* or *synchronous tie*. Thus, HVAC tie line provides a *rigid connection* between any two areas. Even with coordinated control of the AC areas, the operation of the HVAC tie line suffers from three technical problems[3]:(i)Since the interconnection is a synchronous tie, frequency disturbance in one area is transferred to the other area(s).(ii) Power swing in one area affects the other area(s) in the interconnected system since large power swings may result in frequency tripping. Further ,major faults in any of the areas network may lead to complete failure of the whole multi area system .(iii)There is increased fault level if an existing AC area is interconnected with another AC area(s) by HVAC tie line. This is because the additional parallel lines reduce the equivalent reactance of the interconnected system .

HVDC interconnections or HVDC tie lines provide a *loose coupling* between the two interconnected areas. This is called *non-synchronous (asynchronous) tie line*. This interconnection has four merits [3]:(i) Since the HVDC tie lines between the areas is asynchronous, the two areas can either operate at the same frequency or may have different frequencies. This facilitates interconnection of AC systems at different frequencies to enable them operate independently and to maintain their frequency standards. (ii) HVDC link provides fast and reliable control of magnitude and direction of power flow by controlling the firing angle of the converters. The rapid control of power flow increases the limit of transient stability in the multi area system. (iii) Further, power swings in the interconnected AC networks can be damped rapidly by modulating the power flow through the HVDC line. Thus the stability of the multi area system is increased. (iv) Fault level in each dynamic area remains unchanged.

A multi terminal DC (MTDC) has more than two converter stations and interconnecting DC transmission lines. Radial MTDC is the HVDC system of choice for the multi area asynchronous tie lines in this paper because of the following reasons[3,4]: (i)It is more flexible and economical (iii)Frequency oscillations in the areas can be damped quickly(iii) There is inherent overload capability. Hence transient stability of the interconnected system is increased without an increase in installed capacity. Thus, the overall stability of the multi area system is improved. (iv)Heavily loaded AC area networks can be reinforced by using MTDC systems

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 [5]

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

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, 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: Similarly, 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

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

MTDC Tie Line Losses Cost Function: The transmission cost in MAMODED for power transfer between areas using MTDC tie lines 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 MTDC 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

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

$$F(E) = \sum_{m=1}^{M}\sum_{y=1}^{Y}(\beta_{3,ym}P_{t,ym}^3 + \beta_{2,ym}P_{t,ym}^2 + \beta_{1,ym}P_{t,ym} + \beta_{0,ym} + \zeta_{3,ym}\exp(\lambda_{3,ym}\,P_{ym}) + \zeta_{2,ym}) \quad (5)$$

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 equations (1)-(5), the overall operational cost for MAMODED with thermal and renewable units, tie line losses and emissions can be formulated as

$$F = h[F(P_{i,m}) + F(w_{ijm}) + F(PV_{ijm}) + F(T)] + (1-h)F(E) \quad (6)$$

Where h is the weighting factor

B: Constraints

a) System Constraints (SC)

- Import export area power balance constraint(IEAPBC)

$$\sum_{m=1}^{M}\sum_{y=1}^{Y}P_{i,m} - \sum_{m=1}^{M}\sum_{i=1}^{N_d}P_{Da,im} - \sum_{k,k\neq m}T_{mk} = 0 \quad m = 1,2,\dots M \quad (7)$$

where N_d the number of loads in area m, T_{mk} is the total MTDC 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)

$$\sum_{y=1}^{Y}S_{i,m} \geq S_{req,m} + \sum_{k,k\neq m}R_{mk} \quad m = 1,2,3\dots M \quad (8)$$

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.

- Thermal unit generation limits (TUGC)

$$P_{im,min} \leq P_{im} \leq P_{im,max} \quad (9)$$

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)

$$P_{im}(t-1) - DR_{im} \leq P_{im} \leq P_{im}(t-1) + UR_{im} \quad (11)$$

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

b) Combined Constraints (CC)

- Net Actual Demand Constraint (NADC)

$$\sum_{m=1}^{M}\sum_{i=1}^{N_d}P_{Da,im} = \sum_{m=1}^{M}\sum_{i=1}^{N_d}P_{Dt,im} - \sum_{m=1}^{M}\sum_{j=1}^{H_w}\sum_{i=1}^{W}w_{ijm,av} - \sum_{m=1}^{M}\sum_{j=1}^{H_S}\sum_{i=1}^{S}PV_{ijm,av} \pm P_R \quad (12)$$

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

$$(PV_{ijm} + w_{ijm})_d \leq xP_{Da,im} \quad (13)$$

- Reserved Power Constraint RPC)

$$P_R \leq (PV_{ijm,av} + w_{ijm,av})_g - (PV_{ijm} + w_{ijm})_d\text{, during}T_a \quad (14)$$

$$P_R \le y \sum_{T_a} \left(PV_{ijm,av} + w_{ijm,av}\right)_g - \left(PV_{ijm} + w_{ijm}\right)_d, \text{during} T_u \quad (15)$$

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

$$\sum_{T_u} P_R \le \sum_{T_a} P_R$$

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[6].

c) HVDC Constraints (HC)

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

$$T_{mk,min} \le T_{mk} + R_{mk} \le T_{mk,max} \quad (16)$$

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

- MTDC Tie Line Flow Constraint(MTLFC)

$$|P_t| \le P_{t,max} \; t = 1,2,3 \dots \dots . N_t \quad (17)$$

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

- MTDC Converter Tap Ratio Constraint (MCTRC)

$$T_{min} \le T \le T_{max} \quad (18)$$

- MTDC Converter Ignition Angle Constraint (MCIAC):Facilitates fast and reliable control of power flows

$$\alpha_{min} \le \alpha \le \alpha_{max} \quad (19)$$

- MTDC Converter extinction Angle Constraint (MCEAC):Facilitates rapid control to increase transient stability limit

$$\gamma_{min} \le \gamma \le \gamma_{max} \quad (20)$$

- HVDC Current Constraint (HCC)

$$I_{dc,min} \le I_{dc} \le I_{dc,max} \quad (21)$$

- HVDC Voltage Constraint (HVC)

$$V_{dc,min} \le V_{dc} \le V_{dc,max} \quad (22)$$

IV: PROPOSED METHODOLOGY

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 [1];

$$y = \sum_{s \epsilon \Omega_s} \pi_s F(X_s) \quad (23)$$

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

$$C_T = \sum_{S,t,m} \pi_s PP_{s,m}(t) \lambda_s(t) + \sum_{i,t,m} C_{im}\left(P_{im}(t)\right) \quad (24)$$

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

$$F = \sum_{S,t,m} \pi_s P_{D,s,m}(t) \lambda_c(t) - C_T \quad (25)$$

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 [9-11].

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 [9]: These include the law of attraction, the law of separation, and the law of objective function [9]. FA is so popular and successful because the method [11]: 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 [12] and using heuristic and deterministic methods to form hybrid FA [13]. 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 [9-13].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

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

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

$$\alpha = \alpha_\infty + (\alpha_0 - \alpha_\infty)e^{-t} \quad (27)$$

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

$$x'_{i+1} = x_i + \beta_0\, r\, e^{-\gamma r^2} + \alpha \text{ sign}\left[rand - \frac{1}{2}\right] \oplus \text{Levy} \quad (28)$$

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 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

$$Levy \sim u = t^{-\lambda}, (1 < \lambda \leq 3) \quad (29)$$

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.

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 [15] .The necessary wind and solar power parameters are as in [14]. 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 [1] 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 MTDC tie-lines' flow limits are as shown in Table 4.0

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

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: MTDC TIE LINE FLOW LIMITS

MTDC Tie Lines	Power(MW)
T_{1-3}	350
T_{1-4}	300
T_{1-5}	350
T_{2-3}	300
T_{3-5}	350
T_{2-4}	350

A: Power cost in 5-Area MAMODE with MTDC Tie Lines

The hourly power cost in scenarios $1 \rightarrow 5$ are as shown in Table 5.0. 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, wind 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 [32]. *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[29]. This is how RE penetration leads to reduced wheeling costs and the variable demand in interconnected systems

B: Emissions in 5-Area MAMODED with MTDC Tie Lines

For the three major emission case, the hourly emissions in ton/h are as shown in table 6.0. The emissions are the highest in area m_5 since all the major emissions are maximally available in the pure thermal base. 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% [29, 32] . 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 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 $0.7 - 1.8\ kg\ CO_2/KWh$[31]. 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. 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

C: MAMODED with MTDC and HVAC Tie Lines

The proposed MAMODED with MTDC was compared with MAMODED with HVAC and the results tabulated in Table 7.0. From the tabulated results, the proposed method results in better emissions and reduced cost in the MAMODED problem for equal number of iterations.

MTDC tie lines led to reduced cost as the line have few conductor and economic conductor size, less corona losses, use of light and cheap towers and reduced line losses (high efficiency and reliability). Reduced emissions are due to the fact that the effects of MTDC interconnections on the existing land is minimized due to reduced right-of-way(ROW) ,hence reduced environmental impact. Other reasons may include reduced corona emissions and reduced tie line conductor and insulator requirement.

TABLE 5.0: POWER COST IN SCENARIOS $1 \rightarrow 5$ (\$/MWh)

Hour (H)	s_1	s_2	s_3	s_4	s_5
t_1	27.09	56.80	62.52	37.75	46.59
t_2	17.60	54.40	50.82	50.37	15.66
t_3	15.58	30.90	47.44	36.50	24.89
t_4	48.30	16.10	10.02	14.33	20.64
t_5	33.03	65.54	40.65	16.92	24.40
t_6	41.51	45.14	95.25	50.23	24.92
t_7	36.47	33.82	23.06	13.51	45.48
t_8	44.36	03.10	61.59	15.56	43.36
t_9	21.41	30.44	21.06	15.31	45.49
t_{10}	20.06	60.82	40.67	20.68	41.14
t_{11}	17.39	30.55	16.98	20.17	36.98
t_{12}	16.55	78.02	27.68	23.19	41.78
t_{13}	23.17	69.48	56.03	15.70	55.91
t_{14}	14.74	33.24	35.22	20.53	51.05
t_{15}	35.00	05.29	21.51	17.50	51.14
t_{16}	48.79	56.65	81.79	20.41	53.94
t_{17}	40.74	33.62	21.25	27.70	51.93
t_{18}	49.28	51.51	30.28	36.69	56.23
t_{19}	33.89	60.01	68.40	46.44	40.14
t_{20}	37.91	50.98	51.79	20.06	37.54
t_{21}	18.03	19.92	56.02	38.74	30.36
t_{22}	17.59	37.50	46.33	17.78	35.36
t_{23}	36.65	60.37	31.41	20.18	27.03
t_{24}	42.08	70.56	17.94	33.72	15.44

D: Comparison of Cost and Emissions during T_a andT_u.

Figure 1.0 shows the percentage change in cost and emissions for a given load curve. The ranges of the times are $0 < T_u 7, 7 < T_a <18$, and $18 < T_u <24$. Three scenarios are considered ;renewable energy and storage(R&S), renewable only (R) and without renewable(N).From the figure , it is clear that 40% of the fuel cost is saved during T_u with both reserve and RE while the saving is less than 20% with only RE.It should be noted that $C_{R\&S} < C_R < C_N$ and $E_{R\&S} < E_R < E_N$.Further the changes in emissions are very small and sometimes negative as compared to the changes in the optimal cost[6].

VI: CONCLUSION

MAMODED problem has been formulated for a hybrid system which includes thermal generating units, solar, wind and renewable reserve with all the possible technical constraints. MTDC lie line which handle RE in a better way have been utilized. 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 and MTDC tie lines is the more efficient and realistic way to fulfill future demand with reduced cost and emissions interconnected systems.

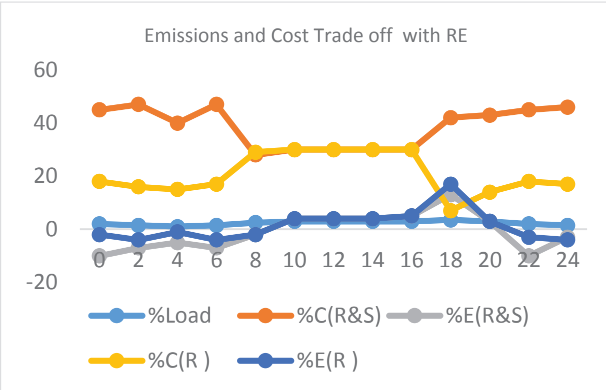

Figure 1.0: Emissions and Cost Trade off

TABLE 6.0: HOURLY EMISSIONS (ton/h)

Hour (H)	m_1	m_2	m_3	m_4	m_5
t_1	4.49	5.15	4.32	4.24	5.52
t_2	3.42	3.05	4.22	3.15	4.45
t_3	5.05	6.58	5.75	6.68	6.08
t_4	4.49	5.13	6.30	5.22	5.52
t_5	1.53	1.11	1.28	1.20	1.56
t_6	5.08	5.63	4.80	4.78	5.00
t_7	-0.24	-1.92	-1.09	-1.05	-1.25
t_8	4.06	3.65	3.82	5.76	4.09
t_9	4.51	4.18	4.35	6.23	5.53
t_{10}	1.09	0.61	0.78	0.72	1.09
t_{11}	-0.32	-1.93	-2.10	-2.05	-1.35
t_{12}	6.51	6.14	6.31	7.19	7.54
t_{13}	1.54	-0.17	-1.33	-1.26	-1.56
t_{14}	6.52	6.23	7.40	6.38	7.56
t_{15}	1.03	0.53	0.70	1.65	1.05
t_{16}	7.03	7.68	6.85	6.80	7.06
t_{17}	1.82	-0.45	-0.62	-0.55	-1.85
t_{18}	7.52	6.17	6.34	7.29	6.56
t_{19}	3.54	3.14	3.31	4.25	4.58
t_{20}	-0.50	-0.17	-0.34	-1.26	-1.52
t_{21}	1.53	1.18	1.33	1.26	1.56
t_{22}	6.55	6.15	7.32	6.28	7.58
t_{23}	1.22	0.58	0.75	0.68	1.08
t_{24}	4.45	4.18	5.35	5.29	5.59

TABLE 7.0: COMPARISON OF MTDC WITH HVAC

Iteration	Optimal Benefit ($)		Emissions (ton/MWh)	
	MTDC	HVAC	HVAC	MTDC
1	2327.48	2303.01	480.78	470.76
2	1960.08	1942.45	81.80	78.50
3	2002.32	1987.11	318.01	310.90
4	2152.01	2140.89	10.00	02.50
5	2187.98	2176.50	981.13	973.86
6	2145.49	2123.66	290.17	280.67
7	2117.37	2101.90	367.20	361.12
8	2123.47	2115.34	464.03	455.65
9	2135.84	2115.60	834.24	819.87
10	2137.85	2128.45	847.93	839.85
11	2133.99	2108.23	99.09	980.87

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