International Journal of Applied Power Engineering (IJAPE)
Vol. 2, No. 3, December 2013, pp. 115~124
ISSN: 2252-8792

Multi Area Economic Dispatch with Tie Line Loss using Secant Method and Tie Line Matrix

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Article Info

Article history:

Received Jan 24, 2013
Revised Jul 12, 2013
Accepted Jul 27, 2013

Keyword:

Economic dispatch
Export and Import
Tie line limits
Tie line Loss
Tie line matrix

ABSTRACT

In this paper, Secant method and tie line matrix are proposed to solve multi area economic dispatch (MAED) problem with tie line loss. Generator limits of all generators in each area are calculated at given area power demands plus export (or import) using secant method and the generator limits of all generators are modified as modified generator limits. Central economic dispatch (CED) problem is used to determine the output powers of all generators and finally power flows in all tie lines are determined from tie line matrix. Here, Secant method is applied to solve the CED problem. A modified tie line matrix is used to find power flow in each tie line and then tie line loss is calculated from the power flow in each tie line. The proposed approach has been tested on two-area (two generators in each area) system and four-area (four generators in each area) system. It is observed from various cases that the proposed approach provides optimally best solution in terms of cost with tie line loss with less computational burden.

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NOMENCLATURE

N	Number of area's
M_j	Number of generators in area 'j'
a_{ji} ,b_{ji} c_{ji}	Cost coefficients of generator 'i' in area 'j'
P_{Gji}	Output power of generator 'i' in area 'j'
P_{Tjk}	Tie line flow (MW) from area j to area k,
fjk	Transmission cost coefficient of P_{Tjk}
$P_{Tjk,min}$	Minimum tie line limit (MW)
$P_{Tjk, max}$	Maximum tie line limit (MW)
FC (P_G)	Fuel cost ($) of generators
F	Total fuel cost
TC (P_T)	Transmission cost ($) of tie lines
P_{Dj}	Power demand of area 'j'
λ_{min}	Minimum incremental fuel cost ($/MW)
λ_{max}	Maximum incremental fuel cost ($/MW)
λ	Incremental fuel cost ($/MW)
$f(\lambda)$	Functional value in terms of 'λ'
P_D	Power Demand (MW)

$Y_{Tie\ line}$	Tie Line matrix
fa(k)	From area ‘k’
ta(k)	To area ‘k’
I_j	Import of area ‘j’
E_j	Export of area ‘j’

1. INTRODUCTION

Economic dispatch (ED) problem is one of the important optimization problems in the economic operation of power systems. The Main objective of the ED problem is to determine the optimal schedule of online generating units so as to meet the power demand at minimum operating cost under various system and operating constraints. This problem is a multi-modal, discontinuous and highly non-linear problem due to the valve point loading, ramp rate limits and prohibited operating zones [1]. Fuel cost function of the generating unit is generally represented by a quadratic function in terms of output power. Many optimization methods such as classical and stochastic search methods have been applied to solve ED problem [2]-[6]. An extensive research has been done to solve the ED problem of a single area, but multi-area economic dispatch (MAED) has received limited attention. Utilities and power pools have limits on power flow between different areas over tie-lines. Each area has its own pattern of load variation and generation characteristics. The objective of MAED problem is determination of the amount of power generation by each generator in a system and power transfer between the areas so as to minimize the total generating cost without violating tie line constraints. Areas of individual power systems are interconnected to operate with maximum reliability, reserve sharing, improved stability and less production cost than operated as isolated area. For real time power system operation, Economic Dispatch(ED) calculation must be taken into account with various types of constraints. Consideration of the transmission capacity among the areas in multi area system while solving economic dispatch problem is one of the important problems in the operation of power system. Tie line limit of tie lines, which are connected between area’s are considered as additional constraints in the MAED problem. Area power demands in each area are specified in the MAED problem. Hence, it is considered as a large scale non-linear problem with various constraints such as generator constraints, tie line limits and etc.

Earlier, some conventional methods [7],[8] were applied to solve the MAED problem. The MAED problem with import/export constraints between areas is addressed by Shoults et al [9]. Complete formulation of multi area generation scheduling is given. Doty et al [10] solved the MAED problem using Spatial Dynamic Programming (SDP). Some initial ideas like an energy brokerage system are addressed in the paper. MAED was solved with area control error and reported in [11]. C. Wang et al [12] proposed a decomposition approach using expert systems for nonlinear multi-area generation scheduling. J. Wernerus et al [13] applied Newton–Rapshon’s method to solve multi-area economic dispatch problem. Dan Streiffert [14] formulated the MAED problem as a capacity constrained nonlinear network flow problem. This method provides a robust, fast and extensible to class of utility problems, but network methods are frequently overlooked. J. Fan et al [15] used quadratic programming to solve the economic dispatch problem with line flow and emission constraints.

Few heuristic, artificial neural networks and hybrid (conventional with heuristic) methods have been recently adopted to solve the MAED problem. T. Yalcinoz et al [16] applied neural network approach to solve the ED problem with tie line constraints. This method has been applied effectively on large scale system. Jayabarathi et al [17] solved the MAED problem using Evolutionary Programming (EP). The EP method finds global or near global solution for small and reasonable size problems. C.L chen et al [18] adopted direct search method for solving the ED problem with tie line limits. This method is tested on various systems with different tie line limits. J.Z Zhu [19] solved the MAED problem using a nonlinear optimization neural network approach.

Recently, modern heuristic methods have been applied to solve the MAED problem with various constraints. Manoharan et al [20] solved the MAED with multiple fuel options using EP. In this paper, the EP is applied as a base level search and then Levenberg Marquardt Optimization (LMO) method is used for fine tuning to determine the optimal solution. This method provides better convergence rate, solution time and optimum cost. Prasanna et al [21] solved multi area security constrained ED using Fuzzy stochastic algorithm. This paper presents two simple, efficient and reliable stochastic algorithms. This method gives accurate optimum value with fast convergence. L. Wang et al [22] proposed particle swarm optimization method for solving MAED problem. A constrained PSO approach is proposed to solve the multi-area electricity market dispatch problem [23]. Differential Evolution with time varying mutation is proposed in [24] to solve the reserve constrained MAED problem. Artificial bee colony optimization has been applied for solving multi-area economic dispatch [25]. The effectiveness of the algorithm has been verified on three different test systems and compared with existing methods.

It has been observed from the literature survey that the conventional, heuristic and hybrid methods have some limitations to provide the best solution within considerable computational time. In this context, a new method (secant method with tie line matrix) is proposed in this paper to solve the multi area economic dispatch problem effectively. The proposed algorithm was implemented in MATLAB (Version 8.0). Rest of the paper is organized in the following sections. Formulation of the MAED problem is introduced in Section 2. Description of the proposed methodology is given in Section 3. Simulation results of various cases are presented in Section 4. The conclusion of the work is presented in Section 5.

2. FORMULATION OF MULTI AREA ECONOMIC DISPATCH (MAED) PROBLEM

Aim of the MAED problem is minimization of the total fuel cost of generators to meet the demands of all areas with tie line constraints.

2.1) Fuel cost

Fuel cost curves of generators are represented by quadratic functions. The total fuel cost *FC* (P_G) is given below.

$$FC(P_G) = \sum_{j=1}^{N}\sum_{i=1}^{M_j}(a_{ji} + b_{ji}P_{Gji} + c_{ji}P_{Gji}^2) \tag{1}$$

Another operational cost in the MAED is the transmission cost of tie line *TC* (P_T) for power transfer between areas. It is expressed as

$$TC(P_T) = \sum_{j=1}^{N-1}\sum_{K=J+1}^{N} f_{jk}P_{Tjk} \tag{2}$$

The total operational cost is

$$F = FC(P_G) + TC(P_T) \tag{3}$$

2.2) Constraints

Various equality and inequality constraints considered in this problem are the generation capacity of each generator, area power balance and tie line limits.

2.2.1) Area power balance constraint:

In area j, the total power generation should be equal to the area power demand P_{Dj} with the consideration of imported and exported power. It is assumed that the tie line loss due to import or export power is neglected. It is expressed as

$$\sum_{i=1}^{M_j} P_{Gij} = P_{Dj} + \sum_{k,k\neq j} P_{Tjk} \tag{4}$$

2.2.2) Generator constraints:

For the power output of generator *i* in area *j* should be between its minimum $P_{Gji,\ \min}$ and maximum $P_{Gji,\ \max}$.

$$P_{Gji,\min} \le P_{Gji} \le P_{Gji,\max} \tag{5}$$

2.2.3) Tie line constraint:

Transfer of the output power from one area to another area should not exceed the tie line limit.

$$P_{Tjk,\ min} \le P_{Tjk} \le P_{Tjk,\ max} \tag{6}$$

2.2.4) Area import/export constraints:

Area import or export constraints should be satisfied while transferring the power through the tie line between the area's. These constraints are given below.

$$\sum_{j=1}^{M_j} P_j \ge P_{Dj} - I_j \tag{7}$$

$$\sum_{j=1}^{M_j} P_j \le P_{Dj} + E_j \quad (8)$$

3. PROPOSED METHODOLOGY FOR MAED PROBLEM WITH TIE LINE LOSS

The following stages are involved in the proposed algorithm to solve the MAED problem with tie line loss.

Stage 1: The range of area power demands for each area is determined by incorporating the tie line limits.
Stage 2: Generator limits of generators at each area power demand are modified for all areas.
Stage 3: Centralized economic dispatch (CED) is used to determine the output powers of all generators in all areas at overall power demand (sum of area power demands).
Stage 4: Export or import power through each tie line is evaluated from the output powers which are obtained from the centralized economic dispatch.
Stage 5: Power flows of all tie lines are determined using Modified Tie line matrix in multi area.
Stage 6: Tie line loss in each is determined from the power flows in each area

The descriptions of each stage are explained below for solving the Multi Area Economic Dispatch problem.

3.1) Determination of range of area power demands by incorporating the tie line limits

Range of area power demands for all area's are determined such that minimum area power demand is area power demand minus area tie line limit and maximum area power demand is area power demand plus area tie line limit. Sometimes, area power demand plus tie line limit exceeds the sum of max powers. In that case, area power demand plus tie line limit should be restricted to the sum of max powers of the generators in the area. Similarly, area power demand minus tie line limit should not be less than the sum of minimum powers of generators in the area.

3.2) Modification of generator limits in each area

At area power demand of area, generator limits of the area are modified as follows,

(i) Output powers of generators in each area are evaluated by secant method at each modified area power demands. Description of the secant method to solve the economic dispatch problem is given in [26],[27].
(ii) Output powers are replaced as generator limits in the cost function.

3.3) Determination of output powers of generators

At overall power demand (sum of the area power demands), the procedure of economic dispatch is used to evaluate the output powers of generators. Here, secant method has been adopted to solve the central economic dispatch. While solving the central ED problem, the generator limits are replaced by modified generator limits.

3.4) Evaluation of Export/Import Tie line power

Export or import power through tie line is evaluated from the following steps**,**

1. Total generation of the area is identified.
2. Difference between total generation and area power demand is calculated.
3. Area incremental fuel cost (λ_{area}) and incremental fuel cost in CED (λ_{sys}) are identified.
4. The following conditions will be taken to get the import and export in each tie line.
   a. $\lambda_{area} < \lambda_{sys}$ then that area export the power through tie line.
   b. $\lambda_{area} > \lambda_{sys}$ then that area import the power through tie line.
5. If the tie line violate the tie line limit during the export or import the power through tie line, then it will be set to maximum tie line limit.

3.5) Determination of Power flow and cost for tie line loss in Each Tie line

It is necessary to find the power flow in each tie line. The following steps have been adopted to find the power flow in each tie line.

3.5. 1) Formulation of Tie line matrix

Tie line matrix gives the information about connectivity of the tie lines in between the area's . The following steps are used to formulate the tie line matrix.

Step 1 System data—Number of area's and number of Tie lines connected, tie line limit and export or import in each area.

Step 2 Initialization of the Tie line matrix ($Y_{Tie\ line}$) (Number of area's × Number of area's)
Step 3 Formation of Diagonal elements and off-diagonal elements
(a) Diagonal elements:
for i=1 to Number of areas
$T_{Tie\ line}$ (i,i)= $T_{Tie\ line}$ (i,i)+ Export or import of the area(i)
end of i th loop
(b) off diagonal elements
for k = 1 to Number of lines
$T_{Tie\ line}$ (fa(k),ta(k)) = $T_{Tie\ line}$ (fa(k),ta(k))+tie_limit(k);
$T_{Tie\ line}$ (ta(k),fa(k)) = $T_{Tie\ line}$ (fa(k),ta(k));
end

It can be observed from the Tie line matrix that the off diagonal elements represent the tie line capacity between the area's and the diagonal elements represents the import or export of the area.

The following steps are used to find the power flow in each tie line.

Step 1 : Input data—export or import power, area incremental lambda's, central lambda and Tie line matrix.
Step 2 : Updating of Import or export powers in each area
(i) Modified Tie line matrix is initialized. Initially, off-diagonal elements are zeros and diagonal elements are export or import of each area in the Modified Tie line matrix.
(ii) If area lambda is less than the central lambda, that area exports the power to the area which is having high area lambda. While exporting the power, tie line should be connected between these two area's. The maximum power exported by the tie line is restricted by the Tie line limit. The updating of the Modified Tie line matrix is given below.
a. The diagonal element of the export area is actual value minus export power and the diagonal element of the import area is actual power plus export power. If the export power is greater than the tie line limit, then the diagonal element of export area is replaced as export power minus tie line limit and the diagonal element of import area is replaced as actual power plus tie line limit.
b. The Off diagonal element (export area to import area) is export power plus existing value. If the export power exceeds the Tie line limit then the excess power will be export to the area which is having next high area lambda.
(iii)The above step is repeated until the export power of the all areas will be zero (diagonal elements in modified tie line matrix are zero).
Step 3 : Off diagonal elements of the modified tie line matrix give the power flow in each area. Assume that the value of $T_{tieline\_modified\ i,j}$ is 100, it indicates that the tie line power flow from area 'i' to area 'j' is 100 MW.

3.6) Determination of cost of Tie line loss

For each Tie line, the loss rate is specified. The tie line loss is product of loss rate of tie line and power flow in the tie line.

4. CASE STUDIES AND SIMULATION RESULTS

The proposed algorithm was implemented in MATLAB (version 8.0) and executed on a Pentium dual core (2.8 GHz) personal computer with 1 GB RAM. In order to prove the effectiveness and applicability of the proposed method, it has been tested on different test systems like two area and four area systems. In order to prove the applicability of the proposed algorithm to solve the MAED problem effectively, it has been tested on large scale system by considering 120 generators.

4.1) Case 1

In this case, two-area system is considered. The fuel cost data of two-area system is obtained from [17] and given in Table 1. In this case, area-1 comprises two generators with power demand of 721 MW and area-2 has two generators with power demand of 309 MW. Two areas are interconnected by a tie line with a limit of 200 MW.

Table 1. Fuel cost data of Two Area system

Area	Generator	a($)	b($/MW)	c($/MW^2)	P_{min}(MW)	P_{max}(MW)
1	1	561	7.92	0.001562	150	600
	2	78	7.97	0.00482	50	200
2	1	310	7.85	0.00194	100	400
	2	250	7.50	0.00184	70	340

The range of power demands and modified power demands for the given tie line limit of 200 MW are given Table 2.

Table 2. Range of power demands by incorporating tie line limit

Area	Power Demands (MW)	Range of power demands after incorporating tie line limit		Modified power demands	
		Minimum power demand	Maximum power demand	Minimum power demand	Maximum power demand
1	721	521	921	521	800
2	309	109	509	170	509

New output powers at modified power demands which are obtained from the secant method are shown in Table 3.

Table 3. Output powers at modified power demands by secant method

Modified P_D(MW)	Area 1 P1(MW)	Area 1 P2(MW)	Modified P_D(MW)	Area 2 P1(MW)	Area 2 P2(MW)
521	397.402	123.5979	170	100	70
800	600	200	509	201.470	307.5291

Table 4. Output powers, total generation in each area, tie line power flow and total fuel cost of the proposed method for two-area system

	Area 1		Area 2	
	P1(MW)	P2(MW)	P1(MW)	P2(MW)
Output powers (MW)	397.402	123.5979	201.4709	307.529
Generation(MW)	521		509	
Area Power demand	721		309	
Incremental fuel cost($/MW)	9.6334		8.254	
Flow(MW)	Import(200 MW)		Export (200 MW)	
Fuel cost ($)	9792.6			

The simulation results such as output powers of generators, total generation in each area, tie line power flow and total fuel cost of the proposed method for two-area system are given in Table 4. The simulation results obtained from the proposed approach have been compared with classical economic dispatch approach with import/export constraints [9] and evolutionary programming [17] and presented in Table 5.

Table 5. Simulation results of classical approach [9], evolutionary programming [17] and proposed method

Area	Generator	Output powers (MW)		
		Conventional method[9]	Evolutionary Programming[17]	Proposed method
1	1	397.41	398.38	397.4021
	2	123.60	122.64	123.5979
2	1	199.03	197.13	201.4709
	2	310.01	311.85	307.5291
Fuel cost($)		9793.05	9792.68	9792.6
Iteration in CED		-	-	3
Solution time (sec)		-	-	0.0012

From the Table 5, it is observed that the proposed approach yields best solution with less computational burden.

4.2) Case 2

In this case, four-area system [14] is considered. In each area, four generators are considered. The loss rate of each tie line per MW is assumed as 0.01 $/MW. Area demands in each area are 400 MW, 200 MW, 350 MW and 300 MW. The Tie line limits of all tie lines are 100 MW. The simulation results of the proposed method for four area system are given in Table 6.

Table 6. Simulation results of the proposed method

Area	Powers (MW) 1	2	3	4	λ_{area} ($/MW)	Flow (MW)	Tie line power flow
1	150	100	66.9	100	8.5556	16.906	Export
2	56.9	96.13	41.81	72.42	7.4615	67.275	Export
3	50	32.04	33.45	33.42	22.0498	-201.0	Import
4	150	100	66.9	100	6.4579	116.90	Export

Incremental fuel cost in central economic dispatch is 9.6905 \$/MW. Therefore, areas-1, 2 and 4 export power and area-3 imports the power. It is specified in the Table 6.

The tie line matrix of the four area system is shown below.

$$T_{Tie\,\text{line Matrix}} = \begin{bmatrix} 16.9045 & 100 & 100 & 100 \\ 100 & 67.27 & 100 & 100 \\ 100 & 100 & -201.07 & 100 \\ 100 & 100 & 100 & 116.9 \end{bmatrix}$$

It can be observed from the $T_{\text{Tie line matrix}}$ that the Tie line matrix gives the information about the connectivity among the areas. Diagonal elements in tie line matrix represent export or import power of the area and the off diagonal elements represent the tie line limit of the tie line, which is connected between the areas. While exporting the power, area 4 violating the tie limit and hence only 100 MW will be transfer to area 3 from area 4. The extra amount of 16.90 is then transfer to area-1. Initially, the elements in modified tie line matrix are assumed such that the diagonal elements are export or import powers and off-diagonal elements are zero. The modified Tie Line matrix at different stages is shown in Table 7.

Table 7. Modified tie line matrix four area system at different stages

Modified Tie Line Matrix (Initial Stage)				Modified Tie Line Matrix (First Stage)			
16.9	0	0	0	0	0	16.9	0
0	67.27	0	0	0	0	67.27	0
0	0	-201.07	0	0	0	-16.9	0
0	0	0	116.9	0	0	100	16.9
Modified Tie Line Matrix (Second Stage)				**Modified Tie Line Matrix (Final Stage)**			
16.9	0	16.9	0	0	0	33.8	0
0	0	67.27	0	0	0	67.27	0
0	0	-16.9	0	0	0	0	0
16.9	0	100	0	16.9	0	100	0

The tie line power flows from one area to another area are shown in Table 8.

Table 8. Power flow in tie lines for four area system

S.no	Tie line Power Flow		Transfer of power	S.no	Tie line Power Flow		Transfer of power
	From	To			From	To	
1	1	2	0	7	3	1	0
2	1	3	33.812	8	3	2	0
3	1	4	0	9	3	4	0
4	2	1	0	10	4	1	16.906
5	2	3	67.275	11	4	2	0
6	2	4	0	12	4	3	100

The simulation results of MAED problem without considering Tie line loss by various methods such as INFP [19], Evolutionary Programming [17] and proposed method are given in Table 9.

Table 9. Simulation results of INFP [19], EP [17] and proposed method

Area	Unit	Output powers (MW)		
		INFP method	Evolutionary Programming	Proposed method
1	1	150	150	150
	2	100	100	100
	3	66.97	65.66	66.906
	4	100	99.9	100
2	1	56.97	57.88	56.906
	2	96.25	93.02	96.132
	3	41.87	42.89	41.816
	4	75.52	71.48	72.421
3	1	50	50.01	50
	2	36.27	36.98	32.044
	3	38.49	40.36	33.453
	4	37.32	38.14	33.425
4	1	150	149.98	150
	2	100	100	100
	3	57.05	56.12	66.906
	4	96.27	97.68	100
Fuel cost($)		7337	7338	7332.2
No of iteration in CED				18
Time (sec)				0.063

The simulation results of MAED problem with Tie line loss by the proposed method is given in Table 10.

Table 10. Simulation results of the MAED problem with tie line loss by proposed method

Fuel cost of Units($)	7332.2
Fuel cost due to Tie line Loss($)	2.01
Total Cost($)	7334.21

5. CONCLUSION

Secant method and Tie line matrix have been proposed in this paper to solve the MAED problem with Tie line loss. A simple procedure is proposed to include the tie line constraints in the ED problem. The proposed method has been tested on various test cases and the simulation results have been compared with the previously reported results such as classical economic dispatch, incremental network flow programming, HNN and evolutionary programming methods. The global results obtained by the method indicate its applicability and validity for solving the MAED problem with Tie line loss.

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