Dynamic Economic Load Dispatch Using Quadratic Programming and GAMS

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***Abstract**: This paper presents a comparative analysis study of an efficient and reliable quadratic programming (QP) and general algebraic modeling system (GAMS) to solve dynamic economic load dispatch (DELD) problem with and without considering transmission losses in a power system. The proposed QP method takes care of different unit and system constraints to find optimal solution. To validate the effectiveness of the proposed QP and GAMS solution, simulations have been performed using four different cases, a 18-unit, 20-unit with losses, 40-unit and a very large system consisting of 110-unit. Results obtained with the QP method and GAMS have been compared with other existing relevant approaches available in literatures. Experimental results show a proficiency of the QP method over other existing techniques in terms of robustness and its optimal search behavior comparing to GAMS.*

Keywords - Economic load dispatch; quadratic programming; general algebraic modeling system

1. INTRODUCTION

Economic load dispatch (ELD) problem concern the determination of the optimal combination of power output for all generating units which will minimize the total fuel cost while satisfying load and operational constraints in power system. ELD is a complex problem to solve because of its massive dimension, a non-linear objective function and large number of constraints. Various investigations on the ELD have been undertaken till date. Suitable improvements in the unit output scheduling can contribute to significant cost savings. To improve the quality of solution, lots of researches have been done and various methods have been evolved so far in the field of ELD [1], [2]. Classical optimization techniques, such as the lambda iteration approach, the gradient method, the linear programming method and Newton's method were used to solve the ELD problem [3]. Lambda iteration method is the most common, which has been applied to solve ELD problems. But for effective implementation of this method, the formulation must be continuous. Though fast and reliable, the main drawback of the linear programming methods is that they are associated with the piecewise linear cost approximation [4].

Artificial Neural Network (ANN) techniques such as Hopfield Neural Network (HNN) [4] have been used to solve ELD for units having continuous or piecewise quadratic fuel cost functions and for units having prohibited zone constraints. Hopfield energy function and numerical iterations are applied to minimize the energy function which is mapped to the objective function of the ELD problem. In the conventional Hopfield Neural Network, the input-output relationship for its neurons is described by sigmoid function. Due to the use of the sigmoid function, the Hopfield model suffers from large computational time and curve saturation. To avoid such problem problems, a linear model is also used [5].

Evolutionary programming (EP), genetic algorithm (GA), differential evolution (DE), particle swarm optimization (PSO) [6], [7] have been also proved to be effective with promising performance etc. Improved fast evolutionary programming algorithm has been successfully applied for solving the ELD problem [1], [5]. Biogeography-Based optimization (BBO) [8], Chaotic particle swarm optimization (CPSO) [9], new particle swarm with local random search (NPSO-LRS) [10], Self-Organizing Hierarchical PSO [11], Bacterial foraging optimization [12], improved coordination aggregated based PSO [13], quantum-inspired PSO [14], improved PSO [15], HHS algorithm [16] and HIGA [17] have been successfully applied to solve the ELD problem.

A comparative analysis study of Quadratic programming (QP) and General Algebraic Modeling System (GAMS) approach is proposed to solve ELD problems. QP is an effective tool to find global minima for optimization problem having quadratic objective function with linear constraints. The objective function for the 4 test system used in the simulation is quadratic but the constraints are not linear. Constraints are liberalized by transformation of variable technique and the QP is applied recursively till the convergence is achieved. GAMS is a high-level model development environment that supports the analysis and solution of mixed integer optimization linear, and non linear problems. GAMS is an accurate tool which can be

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useful easily for large and complex optimization problem.

2. ELD PROBLEM FORMULATION

In a power system, the unit commitment problem has various sub-problems varying from linear programming problems to complex non-linear problems. The concerned ELD problem is one of the different non-linear programming sub-problems of unit commitment. The ELD problem is about minimizing the fuel cost of generating units for a specific period of operation so as to accomplish optimal generation dispatch among operating units and in return satisfying the system load demand considering power system operational constraints.

The objective function corresponding to the production cost can be approximated to be a quadratic function of the active power outputs from the generating units. Symbolically, it is represented as

$$\min F_T(P_G) = \sum_{i=1}^{N} F_i(P_{Gi}) \quad (1)$$

Where the expression for cost function corresponding to i-th generating unit is given by:

$$F_i(P_{Gi}) = a_i P_{Gi}^2 + b_i P_{Gi} + c_i \quad (2)$$

where a_i, b_i and c_i are the cost coefficients; P_{Gi} is the real power output (MW) of i-th generator corresponding to time period t and N is the number of online generating units to be dispatched.

The objective function is subject to the following constraints:

1) Power Balance Constraints:

The total system generation must be equal to the sum total system loads (PD) and losses (PL). That is,

$$P_D + P_L = \sum_{i=1}^{N} P_{Gi} \quad (3)$$

The transmission losses can be expressed using the B-coefficients loss formula

$$P_L(\{P_{Gi}\}) = \sum_{i}^{N}\sum_{j}^{N} P_{Gi} B_{i,j} P_{n2} + \sum_{i}^{N} B_{i,0}.P_{Gi} + B_{0,0} \quad (4)$$

where the parameters {Bi,,j}, {Bi,0}, and B0,0 are B-coefficients known for a specific power system.

By applying Lagrangian multipliers method and Kuhn tucker conditions the following conditions for optimality can be obtained.

$$2a_i P_i + b_i = \lambda\left(1 - B_{i,0} - 2\sum_{j=1}^{N} B_{i,j} P_i\right)(i = 1,2,\ldots,N) \quad (5)$$

2) The Generator Constraints:

The power generated by each generator should be within its lower limit and upper limit so that

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad (6)$$

3) Ramp Rate Constraints:

For convenience in solving the DELD problem, the unit output is usually assumed to be adjusted smoothly and instantaneously. Practically, the operating range of a unit i is restricted by their ramp rate limits (the up-ramp limit Riup and the down-ramp limit Ridown) [5]. Hence, this constraint must be taken into account to achieve true economic operation. The inequality constraints due to ramp rate limits for unit generation changes (ΔPi) between interval t and t+1 of the total periods of operation T are given as follow:

$$P_{Gi}^{t} - P_{Gi}^{t-1} \le R_i^{up} \text{ and } P_{Gi}^{t-1} - P_{Gi}^{t} \le R_i^{down}$$
$$i = 1,\ldots,N \text{ and } t = 1,\ldots,T \quad (7)$$

3. ECONOMIC DISPATCH PROBLEM SOLUTION BY COMPACT QUADRATIC PROGRAMMING

QP is an effective optimization method to find the global solution if the objective function is quadratic and the constraints are linear. It can be applied to optimization problems having non-quadratic objective and nonlinear constraints by approximating the objective to quadratic function and the constraints as linear.

QP is the mathematical problem of finding a vector x that minimizes a quadratic function (23):

$$\min_x\left(\frac{1}{2}\mathrm{x}^T H\,\mathrm{x} + f'\mathrm{x}\right) \quad (8)$$

Subject to the linear inequality and equality (9) and bound constraints (10):

$$\left.\begin{aligned} Ax &\le b \\ A_{eq}x &= b_{eq} \end{aligned}\right\} \quad (9)$$

$$lb \le \mathrm{x} \le ub \quad (10)$$

We use the flowing Matlab code formulated as:

```
x=quadprog (H, f, A, b, Aeq, beq, lb, ub)
% solves the quadratic programming problem:
min 0.5*x'*H*x + f'*x
% while satisfying the constraints
A*x ≤ b
Aeq*x = beq
lb <= x <= ub
```

To map the ED to QP, the objective function variables are given by the power generation output vector (11), the penalized N×N matrix H (12) and the N×1 vector f (13) as follow:

$$x = [P_{G1}, P_{G2}, \ldots, P_{GN}]^T \quad (11)$$

$$H = 2\times\begin{bmatrix} \dfrac{a_1}{1-2B_{11}P_{G1}-B_{01}} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \dfrac{a_N}{1-2B_{NN}P_{GN}-B_{0N}} \end{bmatrix}^T \quad (12)$$

$$f=\left[\frac{b_1}{1-2B_{11}P_{G1}-B_{01}},\ldots,\frac{b_N}{1-2B_{NN}P_{GN}-B_{0N}}\right]^T \quad (13)$$

To satisfy the equality constraint Aeq* x = beq, we set

$$beq \;=\; P_D+(1+z)P_L \quad (14)$$

where PD is a power demand and PL is losses calculated by (4) and z is a controlling parameters.

$$Aeq=[1,1,\ldots,1]+z.\left(x\times\begin{bmatrix}B_{11} & \cdots & B_{1N}\\ \vdots & \ddots & \vdots\\ B_{N1} & \cdots & B_{NN}\end{bmatrix}+ \quad (15)\right.$$

$$\left.[B_{01},\cdots B_{0N}]+[\frac{B_{00}}{P_1},\frac{B_{00}}{P_2},\ldots,\frac{B_{00}}{P_N}]\right)$$

The limits of power generated are imposed in the formulation of QP as follows:

$$lb=[P_{G1}^{\min},\,P_{G2}^{\min},\ldots,P_{GN}^{\min}] \quad (16)$$

$$ub=[P_{G1}^{\max},\,P_{G2}^{\max},\ldots,P_{GN}^{\max}] \quad (17)$$

To map the ED to CQP in Matlab, we propose the following Matlab code:

```
P=1
for i=1:10
        Pl=P'*B*P+B01*P+B00;
        Aeq =ones(1,n)+z*(P'*B+B01+B00/P);
        beq=Pd+(1+z)*Pl;
        ll=diag(1-2*B*P-B01');
        A1=inv(ll)*a;
        f=inv(ll)*b;
        H=2*diag(A1);
P=quadprog(H,f,[],[],Aeq,beq,l,u);
pln=P'*B*P+B01*P+B00;
acu=(Pd+pln)-sum(P);
end
```

The ELD is solved by the following steps.

Step 1: Initialize the procedure, allocate lower limit of each unit, and evaluate the transmission loss PL old.

Step 2: Calculate H, f, beq, Aeq, lb, ub using (12)-(17) respectively.

Step 3: Determine the power allocation of each plant by substitute the quantities of step 2 in the quadratic programming solver to determine the corresponding optimal power generations PGi , i = 1,..,N.

Step 4: Calculate the new value of transmission losses PLnew using (4) by substituting the power generation determined in step 3.

Step 5: Check for convergence

$$\left|P_D+P_L^{new}-\sum_{i=1}^{N}P_{Gi}\right|\le\varepsilon \quad (18)$$

where ε is the tolerance value, for power balance violation.

Step 6: Carry out the steps 2-5 till convergence is achieved.

4. GENERAL ALGEBRAIC MODELING SYSTEM (GAMS)

GAMS is a high-level model specially designed for modeling linear, nonlinear and mixed integer optimization problems. GAMS can easily handle large and complex problems. It is especially useful for handling large complex problems, which may require much revision to establish an accurate model. Models can be developed, solved and documented simultaneously, maintaining the same GAMS model file. The basic structure of a mathematical model coded in GAMS has the components: sets, data, variable, equation, model and output [18] and the solution procedures are shown below

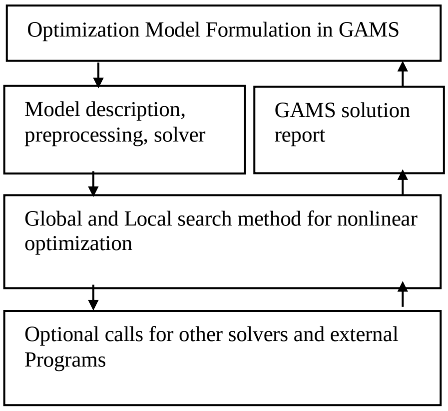

Fig. 1. GAMS modeling and solution procedure.

GAMS formulation follows the basic format as given below:

- **Sets**: Declaration, Assignment of members;
- **Data** (parameters, tables, scalars), Declaration, Assignment of values;
- **Variables**: Declaration, Assignment of type, Assignment of bounds and/or initial values (optional);
- **Equations**: Declaration, Definition;
- **Model and solve statements**;
- **Display statements** (optional)

5. RESULT AND DISCUSSION

The QP and GAMS have been applied on 4 different standard power systems. Test case I is a 18-unit, Test case II is a 20-unit system with losses, Test case III is a 40-unit and Test case IV is a large scale system consisting of 110-unit. The programs were written in MATLAB 7.8 for QP and implementation on GAMS with a Pentium 4 processor and 1GB RAM.

5.1. 18-Unit test system

A 18-unit test system having quadratic cost function: The parameters of all thermal units are taken from [19], and given in Table I. The maximum power demand of the system set at PD = 433.22 MW. The results are compared with λ-iteration and Binary GA [19], RGA [19] and ABC [20] for this system. The summarized and comparative results of test case 1 for different demands (95%, 90%, 80% and 70%) without losses and ramp rate limit constraint for the QP and GAMS algorithm are listed in Table II. From Table II, we can show that QP and GAMS both provides superior result then earlier reported results; but GAMS provides much better result than QP. The summarized and comparative DELD results of case 1 showing the effect of ramp rate limit constraint are given in (1) Table III (between QP and GAMS) (2) Table IV (GAMS with and without ramp rate limit constraint) and (3) Table V showing the comparison results using QP with and without ramp rate limit constraint. The percent changes in results are also given in Table III, Table IV and Table V.

5.2. 20-Unit test system

The system consists of 20-unit having quadratic cost function taking into account transmission losses. Power demand is set at 2500 MW. The parameters of all thermal units and loss coefficient are taken from [21]. The results are compared with λ-iteration and Hopfield Model [21] and BBO [8] methods for this system. The results obtained by QP approach and GAMS are listed in Table II. It can be clearly seen from Table II the proposed GAMS provides better results as compared to other reported evolutionary algorithm techniques like λ-iteration, Hopfield Model, BBO and SA.

5.3. 40-Unit test system

A 40-unit with quadratic cost functions where the input data of the entire system are given in [23]. A load demands of 9000 MW and 10500 MW without transmission losses are considered. The results are compared with VSDE [23] and SA [22] methods for this system. The results obtained by QP approach and GAMS are listed in Table III.

5.4. 110-Unit test system

A large scale system consisting of 110-units system is employed. In this example the fuel cost is modeled by quadratic functions without losses .The input data of the entire system is taken from [24]. To investigate the robustness of the large system, here there are three different demand level of 10000 MW, 15000 MW and 20000 MW are considered. The results are compared with Analytical approach [25], SA [26], SAB [26], SAF [26] and RQEF [27] methods for this system. The results obtained by QP approach and GAMS and the comparative are listed in Table IV. Results of Table IV show that QP and GAMS both provides better results as compared to other reported evolutionary algorithm techniques like Analytical approach, SA, SAB, SAF and RQEA, but GAMS provides much better result than QP.

Table 1. The 18 Unit Test System Characteristics

No	P_i^{min}	P_i^{max}	a_i	b_i	c_i	R^{down} (MW)	R^{up} (MW)
1	7	15.00	0.602842	22.45526	85.74158	10	10
2	7	45.00	0.602842	22.45526	85.74158	10	10
3	13	25.00	0.214263	22.52789	108.98370	10	10
4	16	25.00	0.077837	26.75263	49.06263	10	10
5	16	25.00	0.077837	26.75263	49.06263	10	10
6	3	14.75	0.734763	80.39345	677.73000	5	5
7	3	14.75	0.734763	80.39345	677.73000	10	10
8	3	12.28	0.514474	13.19474	44.390000	10	10
9	3	12.28	0.514474	13.19474	44.390000	10	10
10	3	12.28	0.514474	13.19474	44.390000	10	10
11	3	12.28	0.514474	13.19474	44.390000	10	10
12	3	24.00	0.657079	56.70947	574.96030	10	10
13	3	16.20	1.236474	84.67579	820.37760	10	10
14	3	36.20	0.394571	59.59026	603.02370	7	7
15	3	45.00	0.420789	56.70947	567.93630	10	10
16	3	37.00	0.420789	55.96500	567.93630	10	10
17	3	45.00	0.420789	55.96500	567.93630	10	10
18	3	16.20	1.236474	84.67579	820.37760	3	3

Table 2. Comparision of Economic Load Dispatch Result of 18-Unit System Without ramp rate limit constraint

Demand	λ-iteration ($/hr)[19]	Binary GA ($/hr) [19]	Real coded GA ($/hr) [19]	ABC ($/hr) [20]	QP ($/hr)	GAMS ($/hr)
411.559	29731.05	29733.42	29731.05	29730.8	29731.067	29731.067
389.898	27652.47	27681.05	27655.53	27653.3	27653.750	27653.750
346.576	23861.58	23980.24	23861.58	23859.4	23855.286	23855.286
303.254	20393.43	20444.68	20396.39	20391.6	20386.216	20386.216

Table3. Comparison of DELD result of 18-Unit system with ramp rate limit constraint using QP and GAMS

Time interval	*D*	GAMS			QP			Percent change (%)		
		Total cost	*Losses*	*System λ*	*Total cost*	*Losses*	*System λ*	*Total cost*	*Losses*	*System λ*
1	411.559	29731.067	0.000	100.535	29731.066	0.000	100.535	0,000003	0,0000	0,0000
2	389.898	27654.110	0.000	92.245	27654.098	0.000	92.244	0,000043	0,0000	0,0011
3	346.576	23856.274	0.000	83.817	23856.301	0.000	83.828	-0,000113	0,0000	-0,0131
4	303.254	20389.390	0.000	75.770	20389.449	0.000	75.769	-0,000289	0,0000	0,0013

Table 4. Comparison of DELD result of 18-Unit system using GAMS with and without ramp rate limit constraint

Time interval	D	GAMS with ramp rate limit			GAMS without ramp rate limit			Percent change (%)		
		Total cost	Losses	System λ	Total cost	Losses	System λ	Total cost	Losses	System λ
1	411.559	29731.067	0.000	100.535	29731.066	0.000	100.535	0.000000	0.0000	0.0000
2	389.898	27654.110	0.000	92.245	27653.750	0.000	92.463	0.001302	0.0000	-0.2363
3	346.576	23856.274	0.000	83.817	23855.286	0.000	83.947	0.004141	0.0000	-0.1551
4	303.254	20389.390	0.000	75.770	20386.216	0.000	76.267	0.015567	0.0000	-0.6559

Table 5. Comparison of DELD Result of 18-Unit System Using QP with and without ramp rate limit constraint

Time interval	*D*	QP with ramp rate limit			QP without ramp rate limit			Percent change (%)		
		Total cost	*Losses*	*System λ*	*Total cost*	*Losses*	*System λ*	*Total cost*	*Losses*	*System λ*
1	411.559	29731.066	0.000	100.535	29731.066	0.000	100.535	0,000000	0,0000	0,0000
2	389.898	27654.098	0.000	92.244	27653.750	0.000	92.463	0,001258	0,0000	-0,2374
3	346.576	23856.301	0.000	83.828	23855.286	0.000	83.947	0,004255	0,0000	-0,1420
4	303.254	20389.449	0.000	75.769	20386.215	0.000	76.267	0,015861	0,0000	-0,6573

T**able 6.** Comparison of Result of 20-Unit System (Pd=2500 Mw)

	λ-iteration ($/hr)[21]	Hopfield Model[21]	BBO[8]	QP	GAMS
Power loss (MW)	91.967	91.9669	92.1011	91.9662	91.967
Total generation (MW)	2591.967	2591.9669	2591.1011	2591.9662	2591.967
Power Demand (MW)	2500	2500	2500	2500	2500
Power Mismatch	0	0	0	0	0
Total cost ($/hr)	62456.6391	62456.6341	62456.7926	62456.63309	62456.633

Table 7. Best Power Output for 40-Unit System

	VSHDE [23]	SA [22]	QP	GAMS	VCHDE [23]	SA [22]	QP	GAMS
Total generation (MW)	10500	10500	10500	10500	9000	9000	9000	9000
Power Demand (MW)	10500	10500	10500	10500	9000	9000	9000	9000
Power Mismatch	0	0	0	0	0	0	0	0
Total cost ($/hr)	143943.9	143930.409	143926.424	143926.424	121253.01	121245.164	121244.086	121244.086

Table 8. Comparison of Results for 110-Unit System (Cost ($/H))

Loading condition	Analytical [25]	SA[26]	SAB[26]	SAF[26]	RQEA[27]	QP	GAMS
Low (10000 MW)							
best	1311941.8838	145550.4412	140385.7586	141107.8541	131941.8851		
Average	-----------------	146757.706	141213.4207	141215.1159	131942.0439	131941.8837	131941.8837
worst	-----------------	147476.4295	141900.2431	141398.0923	131942.4931		
Medium (15000 MW)							
best	197988.1775	216100.5475	206921.9057	207380.5164	197988.1393		
average	-----------------	216365.7269	207764.7398	207813.3717	197988.1835	197988.1775	197988.1775
Worst	-----------------	216823.5408	208197.0059	208012.6248	197988.2006		
High (20000 MW)							
Best	313211.5688	314647.0416	313279.8825	314532.8747	313211.5688		
Average	-----------------	315695.1453	314271.7484	314635.3244	313211.5983	313211.5688	313211.5688
Worst	-----------------	317385.2167	314723.8825	314783.5061	313211.8189		

6. CONCLUSION

A QP approach and GAMS for optimization have been used for solving 4 test power systems. Case I is 18-unit with quadratic cost characteristics without transmission loss and considering ramp rate limit constraint, which is investigated by change in percentage of maximum demand (95%, 90%, 80% and 70%) and comparison is made with λ-iteration, Binary GA, RGA and ABC. Based on the simulated results, the QP and GAMS provides superior result than previously reported methods. In case II (20-unit test system) including losses, the obtained results are compared with λ-iteration, Hopfield Model, BBO algorithms. In this case also the QP and GAMS provides superior result than previously reported methods. Case III (40-unit) is investigated through two load demand levels and comparison is made with VSDE and SA. Case IV is a large scale system consists of 110-unit is employed to investigate the robustness of QP method through Three load demand levels. Compared to those obtained with, RGA and SGA and Hybrid GA reported in literature, the result shows that QP and GAMS performs better then above mentioned methods. The QP and GAMS algorithm has superior features, including quality of solution and good computational efficiency, but GAMS provides much better result than QP. The results show that GAMS is a promising technique for solving complicated problems in power system.

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