Economic Dispatch Scheduling using Classical and Newton Raphson Method

Navneet Kaur¹, Maninder², Inderjeet Singh³
¹,²,³Electrical Engineering & PTU, INDIA

ABSTRACT
Over the past several years, concerns have been raised over the possibility that the exposure to 50.60 Hz electromagnetic fields from power lines, substations and other power sources may have detrimental health effects on living organisms. The economic dispatch problem was defined so as to determine the allocation of electricity demand among the committed generating units to minimize the operating costs subject to physical and technological constraints. Economic load dispatch is an important optimization task in power system operation for allocating generation among the committed units such that the system constraints imposed are satisfied and energy requirement in terms of kCal/h or Btu/h or Rupees per hour (Rs/h) are minimized. To all intents and purposes, there has been concern that the economic dispatch may not be the best environmentally. In this research paper economic scheduling of thermal units has been done. Over and above, regular electric supply is the sheer necessity for growing industry and other fields of life.

Keywords------ Economic dispatch, Lambda iteration, Classical Method and Newton Raphson Method.

I. INTRODUCTION
The economic load dispatch problem pertains to the optimum generation scheduling of available generating units in a power system to minimize the cost of generation subject to system constraints [1,2]. In view of rapid growth in demand and supply of electricity, electric power system is becoming increasingly larger and more complex day by day. Regular electric supply is the utmost necessity for growing industry and other fields of life. With the increasing dependence of industry, agriculture and day-to-day household comfort upon the continuity of electric supply, the reliability of power systems has put on great importance [3]. Every electric utility is normally under obligation to provide to its consumers a certain degree of continuity and quality of service (power flow on transmission lines in a specified range). Therefore, economy, emission etc. objectives of the power system must be properly coordinated in arriving at optimal power dispatch[4,5]. It is, therefore, required to search for better and realistic strategies to achieve various objectives along with desired quality of power supply and satisfying simultaneously various system constraints. This implies economic load dispatch scheduling aspects of the system operation, which are duly investigated in the present work in a unified multiojective approach[6].

II. ECONOMIC DISPATCH
Economic dispatch in electric power system has gained increasing importance as the cost associated with generation and transmission of electric energy keeps increasing. So in optimal load dispatch problem generator operating cost characteristics is the most important factor. The major component of generation operating cost for fossil plants is the cost of fuel input per hour, while the cost of maintenance, water etc. contribute only negligibly small portions[7]. The operating characteristics of fossil plants can be expressed in terms of million calories per uneconomical (or may be technically infeasible) to operate the unit and MW.
The power output of the plant is increased sequentially by opening a set of valves at the inlet to its steam turbine. The throttling losses in a valve are large, when it is just opened and small when it is fully opened. As a result the operating cost of a plant has the form as shown in Figure 2.2.

\[ F(P_{gi}) = \sum_{i=1}^{N} \left( a_i P_{gi}^2 + b_i P_{gi} + c_i \right) \text{ Rs/h} \]

(3.1a)

Subject to

(i) The energy balance equation
\[ \sum_{i=1}^{N} P_{gi} = P_D + P_L \]
(3.1b)

(ii) and the inequality constraint
\[ P_{gim} \leq P_{gi} \leq P_{gimax} ; (i = 1,2,\ldots,N) \]
(3.1c)

Where
- \( a_i, b_i, c_i \) are the cost coefficients
- \( P_D \) is the load demand
- \( P_{gi} \) is the real power generation and will act as decision variable
- \( N \) is the number of generation buses
- \( P_L \) is the transmission power loss.

One of the most important, simple but approximate method of expressing transmission loss as a function of generator powers is through B-coefficients. This method uses the fact that under normal operating conditions, the transmission loss is quadratic in the injected bus real powers. The general form of the loss formula using B-coefficients is

\[ P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} B_{ij} P_{gi} P_{gj} \text{ MW} \]

(3.2)

Where, \( P_{gi} \) and \( P_{gj} \) are the real power injections at the ith and jth buses, respectively
- \( B_{ij} \) are the loss coefficients which are constant under certain assumed conditions, \( N \) is number of generation buses.

The transmission loss formula of (3.2) is known as George’s formula.

Another more accurate form of transmission loss expression, frequently known as Kron’s loss formula is...
\[ P_L = B_{00} + \sum_{i=1}^{N} B_{i0} P_{gi} + \sum_{i=1}^{N} \sum_{j=1}^{N} P_{gi} B_{ij} P_{gj} \]  \hspace{1cm} \text{(3.3)}

Where

\[ P_{gi} \] and \[ P_{gj} \] are the real power injections at \( i \)th and \( j \)th buses, respectively.

\[ B_{00}, B_{i0} \] and \( B_{ij} \) are the loss coefficients which are constant under assumed conditions.

\( N \) is the number of the generation buses.

The above constrained optimization problem is converted into an unconstrained optimization problem. Lagrange multiplier method is used in which the function is minimized (or maximized) with side conditions in the form of equality constraints. Using Lagrange multipliers and augmented function is defined as

\[ L(P_{gi}, \lambda) = F(P_{gi}) + \lambda (P_D + P_L - \sum P_{gi}) \]  \hspace{1cm} \text{(3.4)}

Where \( \lambda \) is the Lagrangian multiplier.

Necessary conditions for the optimization problem are

\[ \frac{\partial L(P_{gi}, \lambda)}{\partial P_{gi}} = \frac{\partial F(P_{gi})}{\partial P_{gi}} + \lambda \left( \frac{\partial P_L}{\partial P_{gi}} - 1 \right) = 0 \]  \hspace{1cm} \text{(i=1,2,…….N)}

Rearranging the above equation,

\[ \frac{\partial F(P_{gi})}{\partial P_{gi}} = \lambda \left( 1 - \frac{\partial P_L}{\partial P_{gi}} \right) \]  \hspace{1cm} \text{(i=1,2,…….N)}

\[ \frac{\partial F(P_{gi})}{\partial P_{gi}} \] is the incremental cost of the \( i \)th generator (Rs/MWh)

\[ \frac{\partial P_L}{\partial P_{gi}} \] is the incremental transmission losses.

Equation (3.5) is known as the exact coordination equation, and

\[ \frac{\partial L(P_{gi}, \lambda)}{\partial \lambda} = P_D + P_L - \sum P_{gi} = 0 \]  \hspace{1cm} \text{(3.6)}

Equation (3.5) the so-called coordination equation, numbering \( N \) is solved simultaneously with Eqn. (3.6) to yield a solution for Lagrange multiplier \( \lambda \) and the optimal generation of \( N \) generators.

By differentiating the transmission loss equation Eqn (3.3) with respect to \( P_{gi} \), the incremental transmission loss can be obtained as,

\[ \frac{\partial P_L}{\partial P_{gi}} = B_{i0} + \sum 2B_{ij} P_{gj} \]  \hspace{1cm} \text{(i=1,2,…….N)}

\[ j=1 \]

And by differentiating cost function eqn.(3.1a) with respect to \( P_{gi} \), the incremental cost can be obtained as

\[ \frac{\partial F(P_{gi})}{\partial P_{gi}} = 2a_i P_{gi} + b_i \]  \hspace{1cm} \text{(i=1,2,…….N)}

Equation (3.5) can be rewritten as

\[ \{ \frac{\partial F(P_{gi})}{\partial P_{gi}} \} / (1 - \frac{\partial P_L}{\partial P_{gi}}) = \lambda \]  \hspace{1cm} \text{(3.8)}

or

\[ \{ \frac{\partial F(P_{gi})}{\partial P_{gi}} \} L_i = \lambda \]  \hspace{1cm} \text{(i=1,2,…….N)}

where \( L_i = 1.0/(1-\frac{\partial P_L}{\partial P_{gi}}) \) is called the penalty factor of \( i \)th plant.

To obtain the solution, substitute Eqs. (3.7) and (3.8) into eq (3.5)

\[ 2a_i P_{gi} + b_i = \lambda \left( 1 - B_{i0} - \sum 2B_{ij} P_{gj} \right) \]  \hspace{1cm} \text{(3.9)}

Rearranging the above equation to get \( P_{gi} \), we have

\[ P_{gi} = \frac{\lambda \left( 1 - B_{i0} - \sum 2B_{ij} P_{gj} \right) - b_i}{2(a_i + \lambda B_{ii})} \]  \hspace{1cm} \text{(i=1,2,…….N)}  \hspace{1cm} \text{(3.10)}

\[ j=1 \]  \hspace{1cm} \text{j\#i}

The value of \( P_{gi} \) can obtained as

\[ P_{gi} = \{ \lambda \left( 1 - B_{i0} - \sum 2B_{ij} P_{gj} \right) - b_i \} / 2(a_i + \lambda B_{ii}) \]  \hspace{1cm} \text{(i=1,2,…….N)}

\[ j=1 \]  \hspace{1cm} \text{j\#i}

If the initial values of \( P_{gi} \) and \( \lambda \) are known the above equation can be solved iteratively until eq.(3.6) is satisfied by modifying \( \lambda \). This technique is known as successive approximation.

**IV. ALGORITHM: ECONOMIC DISPATCH (CLASSICAL METHOD)**

1. Read data, namely cost coefficients, \( a_i, b_i, c_i \); B-coefficients, \( B_{ij}, B_{i0}, B_{00} \) \( i=1,2,…….N ; j=1,2,…….N \); convergence tolerance \( \epsilon \), step size \( \alpha \), and maximum iterations allowed, \( IT_{MAX} \), etc.

2. Compute the initial values of \( P_{gi} \) \( i=1,2,…….N \) and \( \lambda \) by assuming that the transmission losses are zero, i.e. \( P_L =0 \)

3. Set iteration counter, \( IT =1 \)

4. Compute \( P_{gi} \) \( i=1,2,…….N \) using eq.(3.10)

5. Compute transmission loss using Eq. (3.3)

6. Compute \( \Delta P = P_D + P_L - \sum P_{gi} \) \( i=1 \)

7. Check \( |\Delta P| \leq \epsilon \), if ‘yes’, then GOTO Step 10.

   Check IT \( \geq IT_{MAX} \), if ‘yes’ then GOTO Step 10.(it means program terminated without obtaining the required convergence).
8. Update $\lambda_{new} = \lambda + \alpha |\Delta P|$, where $\alpha$ is the step size used to increase or decrease the value of $\lambda$ in order to meet the step 6.

9. IT = IT + 1, $\lambda = \lambda_{new}$ and GOTO Step 4 and repeat.

10. Compute optimal total cost from eq.(3.1a) and transmission loss from (3.3).

11. Stop.

V. ECONOMIC DISPATCH USING NEWTON-RAPHSON METHOD

The economic dispatch problem is expressed by eqs.(3.1a), (3.1b) and (3.1c) and is converted into an unconstrained optimization problem as in eq.(3.4). Necessary conditions for the optimization problems eq.(3.4) are given by eqs. (3.5) and eqs (3.6). The solution of nonlinear eq.(3.5) can be obtained using the Newton-Raphson method in which any change in control variables about the initial values can be obtained using Taylor’s expansion. Taylor’s expansion to second order of eq. (3.5) and eq. (3.6) can be written as

$$N \left( \frac{\partial^2 L}{\partial P_g \partial P_g} \right) \Delta P_g + \sum_{j=1}^{N} \left( \frac{\partial^2 L}{\partial P_g \partial P_j} \right) \Delta P_j + \left( \frac{\partial^2 L}{\partial P_g \partial \lambda} \right) \Delta \lambda = -\frac{\partial L}{\partial P_g}$$

(5.1)

$$N \sum_{j=1}^{N} \left( \frac{\partial^2 L}{\partial P_g \partial P_j} \right) \Delta P_j + \left( \frac{\partial^2 L}{\partial \lambda \partial \lambda} \right) \Delta \lambda = -\frac{\partial L}{\partial \lambda}$$

(5.2)

The above equation can be rewritten in matrix form as

$$\begin{bmatrix} \nabla P_g P_g & \nabla P_g \lambda & \nabla \lambda \lambda \end{bmatrix} \begin{bmatrix} \Delta P_g \\ \Delta \lambda \end{bmatrix} = -\begin{bmatrix} \nabla P_g \\ \nabla \lambda \end{bmatrix}$$

(5.3)

Derivatives can be obtained as follows:

$$\frac{\partial L}{\partial P_g} = \partial F_i / \partial P_g + \lambda \left( \partial^2 P_i / \partial P_g \right)$$

$$= \left( \frac{2 a_i P_g + b_i}{N} \right) + \lambda \left( \frac{2 B_i P_g + 1}{N} \right)$$

(i=1,2,...,N) \hspace{1cm} (5.4a)

$$\frac{\partial L}{\partial \lambda} = P_D + P_L - \sum_{i=1}^{N} P_g$$

(i=1,2,...,R and $\Delta \lambda$) \hspace{1cm} (5.4b)

Taking derivatives of eq.(3.14a) with respect to $P_g$, we have

$$\frac{\partial^2 L}{\partial P_g \partial P_g} = \left( \frac{2 a_i + 2 \lambda B_i}{N} \right)$$

(i=1,2,...,NG) \hspace{1cm} (5.5a)

$$\frac{\partial^2 L / \partial P_g \partial \lambda}{\partial P_g} = \lambda \left( \frac{\partial^2 P_i / \partial P_g \partial \lambda}{\partial \lambda} \right) = 2 \lambda B_i$$

(5.5b)

Taking derivatives of eqs. (3.14a) and (3.14 b) with respect to $\lambda$,

$$\left( \frac{\partial^2 L}{\partial \lambda \partial \lambda} \right) = \left( \frac{\partial^2 L / \partial P_g \partial \lambda}{\partial P_g} \right) = \partial P_L / \partial P_g - 1 = B_{g0} + \sum_{i=1}^{NG} 2 B_{ij}$$

(i=1,2,...,NG) \hspace{1cm} (5.5c)

$$\frac{\partial^2 L}{\partial \lambda} = 0$$

(5.5d)

Equations (5.1) and (5.2) are iterated till no further improvement is obtained or single derivatives with respect to control variables become zero.

VI. ALGORITHM: ECONOMIC DISPATCH (NEWTON-RAPHSON METHOD)

1. Read data, namely $a_i$, $b_i$, $c_i$ (cost coefficients); $B_{ij}$, $B_{g0}$, $B_{o0}$ (B-coefficients) (i=1,2,,...,N; j=1,2, ... , N) convergence tolerance, $\epsilon$, and $IT_{MAX}$ (maximum allowed iterations), etc.

2. Compute the initial values of $P_g$ (i=1,2,...,N) and $\lambda$ by presuming that $P_L = 0$.

3. Assume that no generator has been fixed either at lower limit or at upper limit.

4. Set iteration counter $IT = 1$.

5. Compute Hessian and Jacobian matrix elements using eqs (3.14) and (3.15)

$$[H] \Delta P_g = -[J]$$

6. Deactivate row and column of Hessian matrix and row of Jacobian matrix representing the generator whose generation is fixed either at lower limit or at upper limit. This is done so that fixed generators can not participate in allocation.

7. Gauss elimination method is employed in which triangularization and back-substitution processes are performed to find $P_g$ (i=1,2,...,R and $\Delta \lambda$). Here R is the number of generators which can participate in allocation.

$$\sqrt{\sum_{i=1}^{R} \left( \nabla P_g \right)^2} \leq \epsilon$$

or

$$\sqrt{\sum_{i=1}^{R} \left( \frac{\partial P_L}{\partial P_g} \right)^2} \leq \epsilon$$

if convergence condition is ‘yes’ then GOTO Step 10.
    Check IT > ITMAX, if condition is ‘yes’ GOTO Step 10. (it means the procedure
    proceeds without obtaining required convergence).
8. Modify control variables,

\[ P_{gi}^{(\text{new})} = P_{gi} + \Delta P_{gi}; \ (i=1,2, \ldots, \ldots, R) \]  
and \( \lambda^{(\text{new})} = \lambda + \Delta \lambda \)
9. \( IT = IT + 1, P_{gi} = P_{gi}^{(\text{new})}, \lambda = \lambda^{(\text{new})} \) and GOTO Step 5 and repeat.
10. If no more violations then GOTO Step 12, else check the limits of generators
    and fix up as follows:
    If \( P_{gi} < p_{\text{min}} \) then \( P_{gi} = p_{\text{min}} \)
    If \( P_{gi} > p_{\text{max}} \) then \( P_{gi} = p_{\text{max}} \)
11. GOTO Step 4 and repeat.
12. Compute the optimal total cost and transmission loss.
13. Stop.

VII. TEST SYSTEMS AND RESULTS

7.1 Test problem no.1

The fuel inputs per hour of two plants are given as
\[ F_1 (P_{g1}) = (0.00889 P_{g1}^2 + 10.333 P_{g1} + 200) \text{ Rs/h} \]
\[ F_2 (P_{g2}) = (0.00741 P_{g2}^2 + 10.833 P_{g2} + 240) \text{ Rs/h} \]
Determine the economic schedule to meet the demand of 150MW and the corresponding cost of generation. The transmission losses are given by
\[ P_{L} = 0.001 P_{g1}^2 + 0.002 P_{g2}^2 - 2(0.0002 P_{g1} P_{g2}) \]
Assumptions: \( \alpha = 0.05, \quad \varepsilon = 0.0001 \), and ITMAX = 50

Table 7.1 Generation Schedule (Classical Method)

<table>
<thead>
<tr>
<th>IT</th>
<th>( P_{g1} (\text{MW}) )</th>
<th>( P_{g2} (\text{MW}) )</th>
<th>( \lambda (\text{Rs/MW h}) )</th>
<th>( \Delta P (\text{MW}) )</th>
<th>( P_{L} (\text{MW}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>43.4455</td>
<td>22.2245</td>
<td>11.81812</td>
<td>86.819</td>
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<tr>
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<td></td>
<td></td>
<td>06</td>
<td></td>
<td>53</td>
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<tr>
<td>2</td>
<td>119.160</td>
<td>70.5657</td>
<td>16.15907</td>
<td>18.931</td>
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<tr>
<td>3</td>
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<td>15.21250</td>
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<td>19</td>
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<td>4</td>
<td>101.769</td>
<td>61.8196</td>
<td>14.74592</td>
<td>1.8949</td>
<td>15.483</td>
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<td>0.2030</td>
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<td>7</td>
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<td>8</td>
<td>103.301</td>
<td>62.5992</td>
<td>14.86906</td>
<td>0.0213</td>
<td>15.921</td>
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Table 7.2 Generation Schedule (N-R Method)

<table>
<thead>
<tr>
<th>IT</th>
<th>( P_{g1} (\text{MW}) )</th>
<th>( P_{g2} (\text{MW}) )</th>
<th>( \lambda (\text{Rs/MW h}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>104.5631</td>
<td>60.62549</td>
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<td>4.</td>
<td>103.3183</td>
<td>62.60859</td>
<td>14.87035</td>
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POWER LOSS = 15.9269 MW
TOTAL COST = 2309.771 Rs/hr.

Table 7.3(b) B-coefficients MW\(^{-1}\)

<table>
<thead>
<tr>
<th>( \lambda (\text{Rs/MW h}) )</th>
<th>( B_1 )</th>
<th>( B_2 )</th>
<th>( B_3 )</th>
<th>( B_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001363</td>
<td>0.0000175</td>
<td>0.0001839</td>
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<tr>
<td>0.0000175</td>
<td>0.0001545</td>
<td>0.0002828</td>
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<tr>
<td>0.0001839</td>
<td>0.0002828</td>
<td>0.0016147</td>
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Table 7.4 Optimal Generation Schedule (N-R Method)

<table>
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<tr>
<th>IT</th>
<th>( P_{g1} (\text{MW}) )</th>
<th>( P_{g2} (\text{MW}) )</th>
<th>( \lambda (\text{Rs/MW h}) )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>151.2644</td>
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<td>77.67158</td>
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<td>3.</td>
<td>83.27758</td>
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<td>39.54491</td>
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<tr>
<td>4.</td>
<td>83.40215</td>
<td>95.61558</td>
<td>39.48622</td>
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Table 7.5 Generation Schedule (Classical Method)

<table>
<thead>
<tr>
<th>T</th>
<th>I</th>
<th>P_{g1}(MW)</th>
<th>P_{g2}(MW)</th>
<th>P_{g3}(MW)</th>
<th>\lambda(Rs/MWh)</th>
<th>AP(MW)</th>
<th>P_{l1}(MW)</th>
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<tbody>
<tr>
<td>1</td>
<td>78.80</td>
<td>94.88</td>
<td>39.17</td>
<td>11.5185</td>
<td>1.057</td>
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<td>2</td>
<td>80.08</td>
<td>91.61</td>
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<td>80.75</td>
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<td>44.46</td>
<td>11.5368</td>
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<td>9.860</td>
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</tr>
<tr>
<td>4</td>
<td>84.38</td>
<td>96.72</td>
<td>40.48</td>
<td>11.5324</td>
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<td>8.712</td>
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<td>46</td>
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<td>8.712</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>

**POWER LOSS = 8.50394 MW**

**TOTAL COST = 2741.473 Rs/hr.**

**Table 7.5 Generation Schedule (Classical Method)**

<table>
<thead>
<tr>
<th>T</th>
<th>I</th>
<th>P_{g1}(MW)</th>
<th>P_{g2}(MW)</th>
<th>P_{g3}(MW)</th>
<th>\lambda(Rs/MWh)</th>
<th>AP(MW)</th>
<th>P_{l1}(MW)</th>
</tr>
</thead>
<tbody>
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**TOTAL COST = 2741.474 Rs/hr.**

**VIII. CONCLUSION**

Economic dispatch is the short-term determination of the optimal output of a number of electricity generation facilities, to meet the system load, at the lowest possible cost, subject to transmission and operational constraints. The basic constraints of the economic dispatch problem remain in place but the model is optimized to minimize pollutant emission in addition to minimizing fuel costs and total power loss. Due to the added complexity, a number of algorithms have been employed to optimize this environmental/economic dispatch problem. It is concluded that the economic scheduling of thermal units to meet the load demand in the most economic way without violating any system or individual unit constraints.

**REFERENCES**


