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An Efficient Method for Economic Supply of Incremental Power under Deregulation

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ABSTRACT: In a power system a consumer at a bus may want to increase or decrease his load at any point of time.Under deregulation if a private Generation Company at a particular bus alone supplies this additional load it has to supply additional transmission loss which will be different for different Generation Companies located at different buses. So, different incremental generations are required for different generator buses to supply the same incremental load individually. From the declared price for energy($/MWh) of different Generation Companies and their corresponding calculated incremental generations the Transmission Company will be able to choose the cheapest source for this incremental load. On the other hand if a consumer at a particular bus wants to decrease his load the Transmission Company has to calculate the decrement in generation for each generator and to detect the costliest generator bus so that it can decrease the power drawn from that particular Generation Company. In this paper a model is developed to calculate the incremental(decremental) generation required for different generator buses with trivial calculation using the base case load flow result without running any extra load flow thus making it suitable for on-line application.

KEYWORDS: Deregulation,Generation Companies, incremental generation, incremental loss,Jacobean matrix,Newton Raphson load flow

I.INTRODUCTION

Presently privatization and restructuring of Electrical Power System utilities are continuing around the world. Unbundling is taking place to provide independent Generation Companies (GENCO), independent Transmission Companies (TRANSCO) and independent Distribution Companies (DISCO) mainly to inject competition into electric supply. The models of restructuring the utility system are somewhat different at different countries like UK, USA Australia etc. Generation, transmission & distribution activities are separated. The Generation Companies are licensed private companies and are generally connected to a transmission pool or the super-grid system, which feeds distribution networks owned by private companies. Most customers are connected to the distribution networks and some large loads are supplied directly by the Transmission Company i.e. super-grid. In the UK model of privatization customers having load over 100KW could be supplied by any licensed supplier [1]. The opening up of the electricity market has led to some larger users switching suppliers periodically. Under deregulation, Private Generation Companies are quoting price for power every half an hour through Radio and Television [1] and the Transmission Company can purchase power from any Generation Company to supply the load. A consumer wants to increase his load. To supply this additional power if the Transmission Company wants to purchase the total additional power from one Generation Company, additional power to be purchased from Generation Companies will be different for different Generation Companies located at different buses. On the contrary let, a consumer at a particular bus wants to decrease his load. Then Transmission Company has to calculate the decrement in generation for each generator bus when generation is decreased individually and can detect the costliest generator bus so that it can decrease the power drawn from that particular Generation Company, again to maximize economy. Under this context this problem is of great interest for the Transmission Company.

In the existing literature, incremental transmission loss (ITL) analysis has been used for decades for economic load dispatch of electrical power system. Erwin *et al* [2] proposed methodologies to calculate real-time incremental transmission losses for economic load dispatch. Chang *et al* [3] utilizes network sensitivity factors like generation shift distribution factor (GSDF) and line outage distribution factor (ODF) which are established from DC load flow solutions to calculate loss coefficients. Jesus*et al* [4] presented a new method to compute Incremental Transmission Loss (ITL) taking into account the effect of uncertainty on power injections due to measurement errors or future estimation using Fuzzy Set theory. Galiana *et al* [5] proposed Incremental Transmission loss based loss allocation under deregulated

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power system. In all the above literatures for incremental loss calculation the change in transmission loss is computed for change in generations of all the generator buses, instead of increasing the generation at a generator bus at a time.
For loss allocation CERC India [6] uses Marginal Participation and average participation method. In Marginal Participation method, to compensate the incremental changes at the Load node, only one generator responds at a time. But increment in loss is computed by running loadflow and Approved Transmission Charges (ATC) provided by Power Grid Corporation of India. Hardly any researcher have studied to calculate efficiently the incremental loss or incremental generation required at one generator bus only at a time to serve incremental load at a load bus.

At this point an efficient mathematical tool should be developed which can calculate the increment(decrement) in generation at a generator bus to compensate the increment(decrement) in load at a load bus which will be of great use to the transmission company or grid to maximize economy under deregulation.
In this paper we have developed the mathematical model efficiently without running any extra loadflow.

II.PROBLEM FORMULATION

A power system is running at normal state. Let, in the power system no. of buses =n, no. of PV buses =n_{pv}, no. of buses having real power generators =n_g. Let, buses are renumbered so that bus no. 1 is Slack bus, bus no. 2 to (n_{pv}+1) are PV buses, bus number (n_{pv}+2) to bus number n are PQ buses and at bus no 1 to n_g there are generators. Normally, $n_g< n_{pv}<$ n. Under deregulation, Private Generation Companies are quoting price for power every half an hour through Radio and Television. Suppose, the generators at bus no 1 to bus no n_g are owned by independent private companies. A bulk consumer at a particular bus (say, bus no r) needs an additional amount of real power (ΔP_r), henceforth, we call it as incremental load). Suppose, out of n_g no. of generating companies present in the system only one Generation Company has to supply this incremental load. If Generation Company at bus no. 1 supplies this incremental load it has to supply ΔP_1 as incremental generation to thetransmission Company. As there will be increase in transmission loss, so, $\Delta P_1 \rangle \Delta P_r$. If Generation Company at bus q (where, q=2, …., n_g) has to supply this incremental load it requires incremental generation as ΔP_q. Obviously, $\Delta P_1 \neq \Delta P_q$, as incremental transmission loss will be different. The Transmission Company needs to calculate ΔP_q (q= 1,2,……., n_g) so that it can easily choose the most economic supplier for this incremental load to maximize profit.
What is done presently? Load flow is run with bus no. 1 as slack. The specified real power demand at r-th bus increases by ΔPr, reactive power remains same. The specified real and reactive powers at all other PQ buses are same. The specified real powers and voltages at all PV buses are same as in base case. Load flow is run. Slack bus power is calculated. Let, this new slack bus power is $P_{1\,new}$. So, $\Delta P_1 = P_{1new} - P_{1base}$.
For calculating ΔP_q (q=2, 3, …….,n_g), q-th bus becomes Slack bus. The specified real power demand at r-th bus increases by ΔP_r , reactive power remains same. The specified real and reactive powers at all other PQ buses are same. The specified real powers and voltages at all PV buses except q-th bus are same with base case. At bus 1,specified real power is the slack bus power from base case load flow result (P_{1base}). Load flow is run and slack bus power with q-th bus as slack ($P_{q\,new}$) is found out. $\Delta P_q = P_{qnew} - P_{qbase}$. Thus Load flow is run n_g times. The Transmission Company needs to run load flow extra (n_g-1) no. of times to find out cheapest source for this incremental load.
On the contrary let, a consumer at a particular bus wants to decrease his load. Then Transmission Company calculates the decrement in generation for each generator bus when generation is decreased individually by running load flow (ng-1) no of times extra to detect the costliest generator bus.
In this paper we have developed a model by which the transmission Company can calculate the cheapest (costliest) source with trivial calculation using the Jacobean matrix of base loads flow result(which is already available in computer memory) without running load flow any more.

III.MATHEMATICAL MODEL

In the Power flow problem[7], the bus voltage magnitude and angle at Slack bus are known, and also the bus voltage magnitudes at all PV buses are known so we need to calculate the unknown (n-1) no. of bus voltage angles at all PQ & PV buses and (n-1-n_{pv}) no. of bus voltage magnitudes at all PQ buses. The real powers at (n-1) no. of PV & PQ buses

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are specified and reactive powers at all (n-1-n_{pv}) no. of PQ buses are specified. The real powers at PV buses and real & reactive powers at PQ buses can be expressed in terms of unknown bus voltage angles of all PV buses and bus voltage magnitudes and angles of all PQ buses [7]. These are the power flow equations which are highly non-linear and are to be solved to calculate the unknown bus voltage magnitudes and angles. We consider Newton-Raphson load flow using voltage variable in polar co-ordinate. Here, the non-linear power flow equations are linearized around the points of initial estimates to get the linearized equations which relate mismatches in real and reactive powers at different buses to the corrections in voltage angles and Voltage magnitudes of different buses[7-10].

Let, $P_{i\,sp}$ = real power specified at i-th Bus, $P_{i\,cal}$ = real power calculated at i-th Bus, $Q_{i\,sp}$ = reactive power specified at i-th Bus and $Q_{i\,cal}$ = reactive power calculated at i-th Bus. V_i = voltage magnitude at i-th bus, δ_i = voltage angle at i-th bus, ΔP_i = real power mismatch at i-th Bus = $P_{i\,sp} - P_{i\,cal}$, in p.u, ΔQ_i = reactive power mismatch at i-th Bus = $Q_{i\,sp} - Q_{i\,cal}$, in p.u. Mismatches between specified and calculated real powers are determined at (n-1) no. of PV & PQ buses to calculate (n-1) no. of unknown bus voltage angles at these PV&PQ buses. Mismatches between specified and calculated reactive powers are determined at (n-1-n_{pv}) no. of PQ buses to calculate (n-1-n_{pv}) no. of unknown bus voltage magnitudes at these PQ buses. These linearized equations can be written in the matrix form as follows.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \times \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (1)$$

Mismatch Vector Jacobean matrix Correction vector

Where, dimensions of Mismatch Vector(MV)= (2n-2-n_{pv})X1, Jacobean Matrix(JM)=(2n-2-n_{pv}) X (2n-2-n_{pv}) and Correction Vector(CV)= (2n-2-n_{pv})X 1. And ΔP represents sub-vector containing real power mismatches at the PV & PQ buses. ΔQ represents sub-vector containing the reactive power mismatches at the PQ buses. $\frac{\partial p}{\partial \delta}$ represents Sub-matrix containing partial derivatives of real powers of different PV & PQ Buses with respect to voltage angles of PV & PQ Buses, containing terms like $\frac{\partial P_i}{\partial \delta_i}$ and $\frac{\partial P_i}{\partial \delta_j}$ (where j ≠i). $\frac{\partial Q}{\partial \delta}$ represents Sub-matrix containing partial derivatives of reactive powers of different PQ Buses with respect to voltage angles of PV & PQ Buses, containing terms like $\frac{\partial Q_i}{\partial \delta_i}$ and $\frac{\partial Q_i}{\partial \delta_j}$ (where j ≠i). $\frac{\partial P}{\partial V}$ represents Sub-matrix containing partial derivatives of real powers of different PV & PQ Buses with respect to voltage magnitudes of PQ Buses, containing terms like $\frac{\partial P_i}{\partial V_i}$ and $\frac{\partial P_i}{\partial V_j}$ (where j ≠i). $\frac{\partial Q}{\partial V}$ represents Sub-matrix containing partial derivatives of reactive powers of different PQ Buses with respect to voltage magnitudes of PQ Buses, containing terms like $\frac{\partial Q_i}{\partial V_i}$ and $\frac{\partial Q_i}{\partial V_j}$ (where j ≠i). $\Delta\delta$ represents sub-vector containing the corrections in voltage angles of the PV & PQ buses and ΔV represents sub-vector containing the corrections in voltage magnitudes of PQ buses.

In Newton Raphson Load Flow [7-10] at first, we assume initial estimates of bus voltage magnitudes at PQ buses and bus voltage angles at all PV & PQ buses. We calculate real power mismatches at all PV & PQ buses and Reactive power mismatches at all PQ buses. If the maximum value of the magnitude of mismatches calculated are not more than convergence tolerance then we say, that load flow has converged to solution. But if the maximum of mismatch magnitudes are higher than convergence tolerance then we need to update the voltage magnitude and angles using the Newton Raphson load flow model as given in equation (1). For that, at the point of initial estimates we calculate the elements of Jacobean matrix invert it and pre-multiply with the mismatch vector to calculate the correction vector and update the voltage magnitude and angles. Now these updated voltage magnitudes and angles become new estimates for

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voltage magnitudes and angles. The real and reactive power mismatches are calculated. This is called one iteration and this iterative process continues till convergence is reached.

In this model, we add the row corresponding to the mismatch in slack bus power and column corresponding to slack bus voltage angle but then we need to add heavy shunt (10^{6}) at position (1,1) of the Jacobean matrix (i.e. with $\frac{\partial P_1}{\partial \delta_1}$) for musking purpose and make ΔP_1=0. This full Jacobean matrix before adding 10^{6} at (1,1) position having dimension ($2n-1-n_{pv}$)x($2n-1-n_{pv}$) is defined as $J^{(*)}$ and the full Jacobean matrix after adding 10^{6} at (1,1) position having dimension ($2n-1-n_{pv}$)x($2n-1-n_{pv}$) is defined as J $J^{(1)}$. We see in the matrix $\left[J^{(1)}\right]^{-1}$ all the elements in 1st row and all the elements in 1st column are negligible. This will make $\Delta\delta_1 = 0$. The result will be same. At the end of say, iteration K we see that maximum of mismatch magnitudes is not more than convergence tolerance, then we say, load flow has converged in K iterations. At that point (i) the Jacobean ($J^{(1)}$) of order ($2n-1-n_{pv}$) × ($2n-1-n_{pv}$) calculated at K-th iteration, (ii) the Jacobean inverse $[I^{(1)}] = [J^{(1)}]^{-1}$ of order ($2n-1-n_{pv}$) × ($2n-1-n_{pv}$) calculated at K-th iteration, are available in computer memory.

IV.SOLUTION METHODLOGY

Now, these informations in computer memory are used as hidden treasure to calculate the incremental generation required at any plant for any change in incremental demand at any bus. To do so we proceed in the following way.

At first, let us calculate incremental generation required at plant 1, i.e. ΔP_1. Now due to change in load, the voltage profile of the system will change. We need to calculate this change in voltages magnitudes at all PQ buses and angles of all PV and PQ buses. Let, the change in voltage angles are $\Delta\delta_i^{(1)}$ (i=2, 3, …, n) and change in voltage magnitudes are $\Delta V_j^{(1)}$ (j=n_{pv}+2,…, n). Now P_r decreases by ΔP_r, Q_r remains same, keeping P,Q conditions same at all other PQ buses and P,V conditions same at all PV buses, we see the mismatch vector of order ($2n-1-n_{pv}$) × 1 has only one filled in element. As the Jacobean inverse ($I^{(1)} = \left[J^{(1)}\right]^{-1}$)of order ($2n-1-n_{pv}$) × ($2n-1-n_{pv}$) corresponds to bus 1 as Slack so we can use it. The change in voltage angles and magnitudes $\Delta\delta_i^{(1)}$ and $\Delta V_j^{(1)}$ are calculated by pre-multiplying the available Jacobean inverse of order ($2n-1-n_{pv}$) × ($2n-1-n_{pv}$) with the mismatch vector with only one filled in element as shown below.

$$\left[\Delta\delta_1^{(1)}\ \Delta\delta_2^{(1)}\ \Delta\delta_3^{(1)}\ \ldots\Delta\delta_n^{(1)}\ \Delta V_{npv+2}^{(1)}\ldots\ldots\Delta V_n^{(1)}\right]^T = \left[I^{(1)}\right]\left[0\ldots\ldots\ldots\ldots0(-\Delta P_r)\,0\ldots\ldots0\right]^T \quad (2)$$

($2n-1-n_{pv}$) × 1   ($2n-1-n_{pv}$) × ($2n-1-n_{pv}$)   ($2n-1-n_{pv}$) × 1

Only the elements of $I^{(1)}$ in the column corresponding to real power mismatch at r-th bus will be multiplied with ($-P_r$) to give $\Delta\delta_i^{(1)}$ and $\Delta V_i^{(1)}$. Let, $I_{ij}^{(1)}$ denotes the element at ith row and jth column in matrix $I^{(1)}$.

So,

$$\Delta\delta_1^{(1)} = I_{1r}^{(1)}(-\Delta P_r) \qquad \Delta V_{npv+2}^{(1)} = I_{(n+1)r}^{(1)}(-\Delta P_r)$$
$$\Delta\delta_2^{(1)} = I_{2r}^{(1)}(-\Delta P_r) \qquad \ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots \qquad \Delta V_r^{(1)} = I_{(n+r-1-npv)r}^{(1)}(-\Delta P_r)$$
$$\Delta\delta_{q-1}^{(1)} = I_{q\text{-}1r}^{(1)}(-\Delta P_r) \qquad \ldots\ldots\ldots\ldots$$

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$$\Delta\delta_q^{(1)} = I_{q\,r}^{(1)}(-\Delta P_r) \qquad \ldots\ldots\ldots\ldots$$
$$\Delta\delta_{q+1}^{(1)} = I_{(q+1)\,r}^{(1)}(-\Delta P_r) \qquad \Delta V_n^{(1)} = I_{(2n-1-npv)\,r}^{(1)}(-\Delta P_r)$$
$$\ldots\ldots\ldots\ldots$$
$$\Delta\delta_n^{(1)} = I_{n\,r}^{(1)}(-\Delta P_r) \tag{3}$$

$\Delta\delta_1^{(1)}$ will automatically be very small. Now,

$$\Delta P_1 = \frac{\partial P_1}{\partial \delta_2}\Delta\delta_2^{(1)} + \ldots\ldots + \frac{\partial P_1}{\partial \delta_n}\Delta\delta_n^{(1)} + \frac{\partial P_1}{\partial V_{npv+2}}\Delta V_{npv+2}^{(1)} + \ldots\ldots + \frac{\partial P_1}{\partial V_n}\Delta V_n^{(1)} \tag{4}$$

As, $\frac{\partial P_1}{\partial \delta_2} = J_{12}^{(1)}, \frac{\partial P_1}{\partial \delta_n} = J_{1n}^{(1)}, \frac{\partial P_1}{\partial V_{npv+2}} = J_{1(n+1)}^{(1)}, \ldots\ldots\ldots\ldots$ and $\frac{\partial P_1}{\partial V_n} = J_{1(2n-1-npv)}^{(1)}$ (5)

$$\Delta P_1 = -\Delta P_r\left\{\sum_{j=2}^{2n-1-npv} J_{1\,j}^{(1)} I_{j\,r}^{(1)}\right\} = -\Delta P_r\left\{\sum_{j=1}^{2n-1-npv} J_{1\,j}^{(1)} I_{j\,r}^{(1)} - J_{11}^{(1)} J_{1r}^{(1)}\right\} \tag{6}$$

As, matrix $J^{(1)}$ and $I^{(1)}$ are inverse of one another $\sum_{j=1}^{2n-1-npv} J_{1\,j}^{(1)} I_{j\,r}^{(1)}$ equals the value the element at 1st row and r-th column of a unity matrix. As 1≠r, so, $\sum_{j=1}^{2n-1-npv} J_{1\,j}^{(1)} I_{j\,r}^{(1)} = 0$.

Hence,

$$\Delta P_1 = -\Delta P_r\left[-J_{11}^{(1)} I_{1r}^{(1)}\right] = \Delta P_r J_{11}^{(1)} I_{1r}^{(1)} \tag{7}$$

As, $J_{1\,1}^{(1)}$ and $I_{1r}^{(1)}$ are already available in computer memory,using equation (7) we can easily calculate ΔP_1 withoutany requirement of inversion of matrix.

For calculating incremental generation required at any other plant say at bus q (q=2 , …….,n_g) due to an incremental change in demand at r-th bus we proceed as follows.

Now q-th bus becomes slack bus. Let for q-th slack bus case, the change in real and imaginary parts of voltages in q-th bus are $\Delta\delta_i^{(q)}, \Delta V_i^{(q)}$. Obviously $\Delta\delta_q^{(q)} = 0$. We use the Jacobean Matrix($J^{(1)}$ available in computer memory of order (2n-1-n_{pv})×(2n-1-n_{pv}). We add very high value of order of 10^6 to the diagonal elements located at (q, q) position for musking purpose. Let, this be the Jacobean $J^{(q)}$ of order (2n-1-n_{pv}) × (2n-1-n_{pv}). This Jacobean will also guarantee non-singularity. If this Jacobean is inverted to get say, $I^{(q)} = \left[J^{(q)}\right]^{-1}$ of order (2n-1-n_{pv})X(2n-1-n_{pv}) we will see that elements in q-th row and q-th column of $I^{(q)}$ are negligible. Here as q-th bus is Slack, so real power mismatch ΔP_q is put zero. Now the mismatch vector becomes of order (2n-1-n_{pv})X1 with only one filled-in element. Pre-multiplying $I^{(q)}$ with mismatch vector we get the change in voltage angles and magnitudes $\Delta\delta_i^{(q)}$'s (where, i=1,2,…, q-1,q+1,….., n) and $\Delta V_j^{(q)}$'s (where, j=n_{pv}+2,…., n).

$$\left[\Delta\delta_1^{(q)}\ \Delta\delta_2^{(q)}\ \Delta\delta_3^{(q)}\ \ldots\Delta\delta_n^{(q)}\ \Delta V_{npv+2}^{(q)}\ldots\ldots\Delta V_n^{(q)}\right]^T = \left[I^{(q)}\right]\left[0\ldots\ldots\ldots\ldots0(-\Delta P_r)\,0\ldots\ldots0\right]^T \tag{8}$$

(2n-1-n_{pv}) × 1 (2n-1-n_{pv}) × (2n-1-n_{pv}) (2n-1-n_{pv}) × 1

Only the elements of $I^{(q)}$ in the column corresponding to real power mismatch at r-th bus will be multiplied with (-P_r) to give $\Delta\delta_i^{(q)}$ and $\Delta V_i^{(q)}$. Let, $I_{i\,j}^{(q)}$ denotes the element at ith row and jth column in matrix $I^{(q)}$.

So,

$$\Delta\delta_1^{(q)} = I_{1r}^{(q)}(-\Delta P_r) \qquad \Delta V_{npv+2}^{(q)} = I_{(n+1)\,r}^{(q)}(-\Delta P_r)$$

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$$\Delta\delta_2^{(q)} = I_{2r}^{(q)}(-\Delta P_r) \qquad \ldots\ldots.$$

$$\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\ldots\ldots\ldots.. \qquad \Delta V_r^{(q)} = I_{(n+r-1-npv)\,r}^{(q)}(-\Delta P_r)$$

$$\Delta\delta_{q-1}^{(q)} = I_{(q-1)\,r}^{(q)}(-\Delta P_r) \qquad \ldots\ldots\ldots\ldots$$

$$\Delta\delta_q^{(q)} = I_{q\,r}^{(q)}(-\Delta P_r)$$

$$\Delta\delta_{q+1}^{(q)} = I_{(q+1)\,r}^{(q)}(-\Delta P_r) \qquad \Delta V_n^{(q)} = I_{(2n-1-npv)\,r}^{(q)}(-\Delta P_r)$$

$$\ldots\ldots\ldots\ldots$$

$$\Delta\delta_n^{(q)} = I_{n\,r}^{(q)}(-\Delta P_r) \qquad (9)$$

$\Delta\delta_q^{(q)}$ will automatically be very small. Now,

$$\Delta P_q = \frac{\partial P_q}{\partial \delta_1}\Delta\delta_1^{(q)} + \ldots\ldots + \frac{\partial P_q}{\partial \delta_{q-1}}\Delta\delta_{q-1}^{(q)} + \frac{\partial P_q}{\partial \delta_{q+1}}\Delta\delta_{q+1}^{(q)} + \frac{\partial P_q}{\partial \delta_n}\Delta\delta_n^{(q)} + \frac{\partial P_q}{\partial V_{npv+2}}\Delta V_{npv+2}^{(q)} + \ldots\ldots + \frac{\partial P_q}{\partial V_n}\Delta V_n^{(1)} \qquad (10)$$

$$\text{As, } \frac{\partial P_q}{\partial \delta_1} = J_{q1}^{(q)},\ \frac{\partial P_q}{\partial \delta_{q-1}} = J_{q(q-1)}^{(q)},\ \frac{\partial P_q}{\partial \delta_{q+1}} = J_{q(q+1)}^{(q)}\ \frac{\partial P_q}{\partial V_{npv+2}} = J_{q(n+1)}^{(q)},\ \text{and } \frac{\partial P_q}{\partial V_n} = J_{q(2n-1-npv)}^{(q)} \qquad (11)$$

$$\Delta P_q = -\Delta P_r\left\{\sum_{j=1,\, j\neq q}^{2n-1-npv} J_{q\,j}^{\ (q)} I_{j\,r}^{\ (q)}\right\} = -\Delta P_r\left\{\sum_{j=1}^{2n-1-npv} J_{q\,j}^{\ (q)} I_{j\,r}^{\ (q)} - J_{q\,q}^{\ (q)} J_{q\,r}^{\ (q)}\right\} \qquad (12)$$

As, matrix $J^{(q)}$ and $I^{(q)}$ are inverse of one another $\sum_{j=1}^{2n-1-npv} J_{q\,j}^{\ (q)} I_{j\,r}^{\ (q)}$ equals the value the element at q-th row and r-th column of a unity matrix. As q≠r, so, $\sum_{j=1}^{2n-1-npv} J_{q\,j}^{\ (q)} I_{j\,r}^{\ (q)} = 0$.

Hence,

$$\Delta P_q = -\Delta P_r\left[-J_{qq}^{(q)} I_{q\,r}^{(q)}\right] = \Delta P_r J_{qq}^{(q)} I_{qr}^{(q)} \qquad (13)$$

(for q=2, 3, …., ng)

In equation (13), ΔP_r and $J_{q\,q}^{(q)}$ are known, $I_{q\,r}^{(q)}$ is to be calculated.So instead of evaluating all the elements of $I^{(q)}$ we need only one element i.e. the element at q-th row and r-th column of $I^{(q)}$. Thus very little computational time is required compared to running one load flow. From the declared price for energy ($/MWh) of different Generation Companies and their corresponding calculated incremental generations the Transmission Company will be able to choose the cheapest source for this incremental load.

Instead of increase in load if load decreases at any load bus say at bus r by an amount ΔP_{rd} then we put $\Delta P_r = -\Delta P_{rd}$ in equation (7) and (13) and calculate ΔP_1 and ΔP_q and we see they will be negative indicating the decrement in generation required for individual generator bus. Then from declared price for energy ($/MWh) of individual generation companiesand their corresponding decrement in generation, the grid operator or transmission company can detect the costliest generatorso that it can decrease the power drawn from that particular Generation Company, again to maximize economy.

V. CASE STUDIES AND FINDINGS

Studies on 4 bus system [11] having 2 generator buses, IEEE 14 bus system [12] having 2 generator buses and 30 bus system [13] having 6 generator buses are provided here. The incremental change in demand may take place at any bus. To show the robustness of the proposed model we have considered the incremental load to take place at bus having poorest voltage condition. For 4 bus system bus no. 4 has poorest voltage at base case load flow so, we consider the incremental change in demand to take place at 4th bus. For 14 bus system bus no. 14 has poorest voltage at base case load flow so, we consider the incremental change in demand to take place at 14th bus. For IEEE 30 bus system bus no.

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30 has poorest voltage at base case load flow so, we consider the incremental change in demand to take place at 30thbus. Let, the amount of incremental change in demand for both cases is 0.01 p.u. MW. To show the robustness of the proposed model we compare the incremental generation value calculated using the model with the actual incremental generation required as calculated by running load flow by changing the slack bus. The comparison is given in table.1. Here we see that the error in calculation is practically negligible for all the systems i.e. our model is very fast and accurate. If incremental change takes place in any other the accuracy will be even higher.

Table 1: Comparison of incremental generation calculated by the proposed model with that calculated by running load flow by changing the slack bus.

Convergence Tolerance=0.0001p.u. Mw & MVar. Incremental Demand=0.01 p.u. Mw.					
Test System	Incremental demand occurs at bus no.	Supplier	Incremental Generation Calculated by		Error(%)= (actual-calculated) / actual X 100%
			Actual(by running Load flow)	the proposed method	
4 bus	Bus no. 4	Generator 1	0.010464	0.010453	-0.105%
		Generator 2	0.010240	0.010235	-0.05%
IEEE 14 bus	Bus no 14	Generator 1	0.011387	0.011375	-0.105%
		Generator 2	0.010792	0.010781	-0.102%
IEEE 30 bus	Bus no 30	Generator 1	0.011290	0.011257	-0.292%
		Generator 2	0.010954	0.010923	-0.283%
		Generator 3	0.010323	0.010293	-0.291%
		Generator 4	0.010559	0.010537	-0.208%
		Generator 5	0.010557	0.010534	-0.218%
		Generator 6	0.010686	0.010663	-0.215%

Using the proposed model the incremental generation required at any plant for an incremental change in customer demand at a bus having poorest voltage profile can be calculated with high accuracy. If the proposed model is to calculate the incremental generation required at any plant for an incremental change in customer demand at any other bus accuracy will be higher. So, instead of running load flow (n_g -1) times extra with little computational burden we can calculate the incremental generation accurately.

VI. CONCLUSION

At any given base load condition a consumer wants to have additional load. The incremental generation required at any generating plant to serve this additional load single-handed the Transmission Company needs one extra load flow to run. So for a power system having n_g no. of generators (n_g-1) no. of extra load flow is to be run to select the cheapest source for the incremental load. But if the Transmission Company uses the proposed model the incremental generations required at different plants at different buses can be calculated from base load flow with little extra computational burden. From the calculated incremental generations of different Generation Companies and their corresponding declared price for energy($/MWh) the Transmission Company will be able to choose the cheapest source for this incremental load. So the proposed model is highly computationally efficient and suitable for on-line application so as to maximize the Transmission Company's profit. This model is helpful for the Bulk Consumer also to select the cheapest source for this incremental load so as to minimize the cost of incremental power. On the other hand if a consumer wants to decrease the load at a particular bus the Transmission Company can easily detect the generator from which the purchase of power is costliest so that it can decrease the power drawn from that particular Generation Company, again to maximize profit. Similarly, the Bulk Consumer can easily detect the generator from which the purchase of power is costliest so that it can decrease the power drawn from that particular Generation Company, again to minimize cost of power. The outcome of the proposed model is compared with the well known results of load flow of IEEE standard systems and found adequately accurate.

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