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Simplified technique for Newton-Raphson power flow solution in polar form using hybrid bus

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This paper proposed a novel load flow technique using Newton-Raphson (NR) polar form method with hybrid bus. In the former literature bus admittance matrix, Y_{Bus} , is used for the computation of the load flow problems, that will take more number of iterations to converge the problem. To overcome this drawback, in this paper a novel NR polar form method using hybrid bus,H_{Bus} is proposed. The NR polar form load flow equations using H_{Bus} are derived. Standard IEEE test system and Indian utility systems are used to demonstrate the performance of the proposed approach. The results for NR power flow problem are physically interpreted on the IEEE-30 bus, 103 and 140 Indian utility bus systems with supporting numerical and graphical results and also validated against existing methods. The results using proposed approach show their superiority over existing approaches.

Keywords: *Load flow solution; bus hybrid matrix; Newton-Raphson method; power system.*

1.0 INTRODUCTION

For all power system operation and planning load flow calculations are mostly used. In order to predict next step in power system operation and control generally power flow analysis or contingency analysis are performed. LU Decomposition of Jacobian matrix remains the most computationally expensive task in NR iterative process. n [1], presents application of proposed combined Newton–Raphson method which is based on convergence rate control. In [2] presents a comparative analysis of the influence of PV bus representation on the convergence characteristics of the Newton- Raphson Current Injection method. The methods used for solving the power flow problem are based on current injection equations written in polar coordinates. In [3] proposed Newton–Raphson method for current-based model presented. In [4] proposed new model which approximate the AC load flow problems, the pseudo-load flow solution can provide useful information to assist in locating the cause of infeasibility of the AC load flow model. In [5], proposed modelling an Interline power flow controller (IPFC) for power flow calculations by applying the Newton-Raphson method was presented. Improvements and modification of the existing systems are represented in [6-11]. In general power flow problem can be solved using bus impedance matrix or bus admittance matrix and or the combination of admittance and impedance matrix H_{Bus} [12] presented. In [13-14] different combinations of buses are available to form the H_{Bus} in rectangular form.

In general there are two methods are used conventionally for forming the HBus. One is transformation through the relation between the parameters [15], in this method, either

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bus admittance matrix or bus impedance matrix has to form fist and then transformed to HBus. Second one is using tearing algorithm [16-18], in this method first total system network is divided into sub networks and their solutions are coordinated to achieve the total solution. Above two methods are chronic. From the above literature it is observed that bus admittance matrix is used for solution of load flow problems, this will give large convergence time. And also some of the literature used hybrid bus for solving load flows in NR method in rectangular form, this require large memory storage capacity. To overcome the above drawbacks in this paper proposed hybrid bus in polar form is used

$$\begin{bmatrix} \bar{E}_i - E_{slack} \\ \bar{I}_k \end{bmatrix} = \begin{bmatrix} H_{ii} & H_{ik} \\ H_{ki} & H_{kk} \end{bmatrix} \begin{bmatrix} \bar{I}_i \\ \overline{E_k} - E_{slack} \end{bmatrix}$$

Where i =1,2,3,.......m,
k=m+1,m+2,.......,m+n;
m and n are the number of buses in impedance and admittance form.
E_s is the slack bus voltage.
Formation of the bus hybrid matrix is described in [12]

2.0 NR POWER FLOW EQUATIONS IN POLAR FORM USING HYBRID BUS

The NR equations for real and reactive power in polar form using hybrid bus are derived as follows:

Let us 1 be the reference bus in Polar form and also V = |V| ejδ and H =|H|ejθ

Here P_i is the real power at the ith bus and Q_i is the reactive power at the ith bus.

2.1 Equations for the buses that are in impedance form

From the hybrid performance equation the voltage at the rthbus, which is in impedance form, is

$$|V_r|e^{j\delta_r} - |V_s|e^{j\delta_s} = \sum_{i=1}^{p} |H_{ri}|e^{j\theta_{ri}} \frac{(P_i - jQ_i)}{|V_i|e^{-j\delta_i}} - \sum_{n=p+1}^{p+q} |H_{rn}|e^{j\theta_{rn}} (|V_n|e^{j\delta_n} - |V_s|e^{j\delta_s})$$

for power flow study using the NR method. In this requirement of memory storage capacity is less compared to existing approaches and also observed that it requires less number of iterations compared to existing methods.

3.0 POWER FLOW USING HYBRID BUS

The methods of using the hybrid bus model take advantage of the sparsity of matrices to help faster convergence [13].

The performance equation using H_{Bus}

$$= |H_{rr}|I_r + \sum_{\substack{i=1 \\ i\neq r}}^{p} |H_{ri}|e^{j\theta_{ri}} \frac{(P_i - jQ_i)}{|V_i|e^{-j\delta_i}} - \sum_{n=p+1}^{p+q} |H_{rn}|e^{j\theta_{rn}} (|V_n|e^{j\delta_n} - |V_s|e^{j\delta_s}),$$

$$where\ I_r = \frac{1}{|H_{rr}|e^{j\theta_{rr}}} \Big[|V_r|e^{j\delta_r} - |V_s|e^{j\delta_s} - \frac{(P_i - jQ_i)}{|V_i|e^{-j\delta_i}} - \sum_{n=p+1}^{p+q} |H_{rn}|e^{j\theta_{rn}} (|V_n|e^{j\delta_n} - |V_s|e^{j\delta_s}) \Big]$$

$$and\ P_r - jQ_r = V_r^{*} I_r = |V_r|e^{-j\delta_r} \Big\{ \frac{1}{|H_{rr}|e^{j\theta_{rr}}} \Big[|V_r|e^{j\delta_r} - |V_s|e^{j\delta_s} - \sum_{i=1}^{p} |H_{ri}|e^{j\theta_{ri}} \frac{(P_i - jQ_i)}{|V_i|e^{-j\delta_i}} - \sum_{n=p+1}^{p+q} |H_{rn}|e^{j\theta_{rn}} (|V_n|e^{j\delta_n} - |V_s|e^{j\delta_s}) \Big] \Big\} =$$

$$\frac{|V_r|}{|H_{rr}|} e^{-j(\delta_r + \theta_{rr})} \Big\{ |V_r|e^{j\delta_r} - |V_s|e^{j\delta_s} - \sum_{\substack{i=1 \\ i\neq r}}^{p} \frac{|H_{ri}|}{|V_i|} e^{j(\theta_{ri} + \delta_i)} (P_i - jQ_i) - \sum_{n=p+1}^{p+q} \Big[|H_{rn}||V_n|e^{j(\theta_{rn} + \delta_n)} - |H_{rn}||V_s|e^{j(\theta_{rn} + \delta_s)} \Big] \Big\}$$

$$= \frac{|V_r^2|}{|H_{rr}|} e^{-j(\theta_{rr})} - \frac{|V_r||V_s|}{|H_{rr}|} e^{-j(\delta_r + \theta_{rr} - \delta_{ss})} - \sum_{\substack{i=1 \\ i\neq r}}^{p} \Big[\frac{|V_r||H_{ri}|}{|H_{rr}||V_i|} P_i e^{-j(\delta_r + \theta_{rr} - \theta_{ri} - \delta_j)} - j \frac{|V_r||H_{ri}|}{|H_{rr}||V_i|} Q_i e^{-j(\delta_r + \theta_{rr} - \theta_{ri} - \delta_j)} \Big] - \sum_{n=p+1}^{p+q} \Big[\frac{|V_r||H_{rn}||V_n|}{|H_{rr}|} e^{-j(\delta_r + \theta_{rr} - \theta_{ri} + \delta_n)} - \frac{|V_r||H_{rn}||V_s|}{|H_{rr}|} e^{-j(\delta_r + \theta_{rr} - \theta_{ri} + \delta_s)} \Big]$$

$$= \frac{|V_r^2|}{|H_{rr}|}(\cos\theta_{rr} - j\sin\theta_{rr})$$
$$- \frac{|V_r||V_s|}{|H_{rr}|}[\cos(\delta_r + \theta_{rr} - \delta_s)$$
$$- j\sin(\delta_r + \theta_{rr} - \delta_s)]$$
$$- \sum_{\substack{i=1\\ i\neq r}}^{p}\left[\frac{|V_r||H_{ri}|}{|H_{rr}||V_i|}P_i[\cos(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)\right.$$
$$- j\sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)]$$
$$- j\frac{|V_r||H_{ri}|}{|H_{rr}||V_i|}Q_i[\cos(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)$$
$$\left. - j\sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)]\right]$$

$$- \sum_{n=p+1}^{p+q}\left[\frac{|V_r||H_{rn}||V_n|}{|H_{rr}|}[\cos(\delta_r + \theta_{rr} - \theta_{ri}\right.$$
$$+ \delta_n) - j\sin(\delta_r + \theta_{rr} - \theta_{ri} + \delta_n)]$$
$$- \frac{|V_r||H_{rn}||V_s|}{|H_{rr}|}[\cos(\delta_r + \theta_{rr} - \theta_{ri} + \delta_s)$$
$$\left. - j\sin(\delta_r + \theta_{rr} - \theta_{ri} + \delta_s)]\right]$$

By comparing the real and imaginary parts from the eqns. (3) and (4) the real power is given as

$$P_r = \frac{|V_r^2|}{|H_{rr}|}\cos\theta_{rr}$$
$$- \frac{|V_r||V_s|}{|H_{rr}|}\cos(\delta_r + \theta_{rr} - \delta_s)$$
$$- \sum_{\substack{i=1\\ i\neq r}}^{p}\left[\frac{[V_r][H_{ri}]}{|H_{rr}||V_i|}P_i\cos(\delta_r\right.$$
$$+ \theta_{rr} - \theta_{ri} - \delta_i)$$
$$- \frac{[V_r][H_{ri}]}{|H_{rr}||V_i|}Q_i\sin(\delta_r + \theta_{rr}$$
$$\left. - \theta_{ri} - \delta_i)\right]$$
$$- \sum_{n=p+1}^{p+q}\left[\frac{[V_r][H_{ri}]|V_n|}{|H_{rr}|}\cos(\delta_r\right.$$
$$+ \theta_{rr} - \theta_{ri} + \delta_n)$$
$$- \frac{[V_r][H_{ri}]|V_n|}{|H_{rr}|}\cos(\delta_r + \theta_{rr}$$
$$\left. - \theta_{ri} + \delta_s)\right]$$

After taking the common term outside, the equation (5) is modified as

$$P_r = \frac{1}{|H_{rr}|}\left\{|V_r^2|\cos\theta_{rr}\right.$$
$$- |V_r||V_s|\cos(\delta_r + \theta_{rr} - \delta_s)$$
$$- \sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}[|V_r||H_{ri}|P_i\cos(\delta_r$$
$$+ \theta_{rr} - \theta_{ri} - \delta_i)$$
$$- |V_r||H_{ri}|\,Q_i\sin(\delta_r + \theta_{rr}$$
$$- \theta_{ri} - \delta_i)]$$
$$- \sum_{n=p+1}^{p+q}[|V_r||H_{rn}||V_n|\cos(\delta_r$$
$$+ \theta_{rr} - \theta_{ri} + \delta_n)$$
$$- |V_r||H_{rn}||V_s|\cos(\delta_r + \theta_{rr}$$
$$\left. - \theta_{ri} + \delta_s)]\right\}$$

The reactive power is given as

$$Q_r = \frac{|V_r^2|}{|H_{rr}|}\sin\theta_{rr}$$
$$- \frac{|V_r||V_s|}{|H_{rr}|}\sin(\delta_r + \theta_{rr} - \delta_s)$$
$$- \sum_{\substack{i=1\\ i\neq r}}^{p}\left[\frac{[V_r][H_{ri}]}{|H_{rr}||V_i|}P_i\sin(\delta_r\right.$$
$$+ \theta_{rr} - \theta_{ri} + \delta_n)$$
$$+ \frac{[V_r][H_{ri}]}{|H_{rr}||V_i|}Q_i\sin(\delta_r + \theta_{rr}$$
$$\left. - \theta_{ri} - \delta_i)\right]$$

$$- \sum_{n=p+1}^{p+q}\left[\frac{[V_r][H_{rn}]|V_n|}{|H_{rr}|}\sin(\delta_r\right.$$
$$+ \theta_{rr} - \theta_{ri} + \delta_n)$$
$$- \frac{[V_r][H_{rn}]|V_s|}{|H_{rr}|}s\,in(\delta_r + \theta_{rr}$$
$$\left. - \theta_{ri} + \delta_s)\right]$$

By taking the common term outside, the equn.(7) is modified as

$$Q_r = \frac{1}{|H_{rr}|}\left\{|V_r^2| \sin\theta_{rr} - |V_r||V_s| \sin(\delta_r + \theta_{rr} - \delta_s) - \sum_{\substack{i=1\\ i\neq r}}^{p} \frac{1}{|V_i|}[|V_r||H_{ri}|P_i \sin(\delta_r + \theta_{rr} - \theta_{ri} + \delta_n) + |V_r||H_{ri}|\, Q_i \sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)] - \sum_{n=p+1}^{p+q} [|V_r||H_{rn}||V_n| \sin(\delta_r + \theta_{rr} - \theta_{ri} + \delta_n) - |V_r||H_{rn}||V_s| \sin(\delta_r + \theta_{rr} - \theta_{ri} + \delta_s)]\right\}$$

3.1 Equations for the buses that are in admittance form

Similarly for the buses that are in admittance form, from the hybrid performance equation,

$$I_t = \sum_{i=1}^{p} H_{ti} I_i + \sum_{n=p+1}^{p+q} H_{ti}(V_n - V_s)$$

$$P_t - jQ_t = |V_t|e^{-j\delta_t}\left[\sum_{i=1}^{p}|H_{ti}|e^{j\theta_{ti}}\frac{(P_i - jQ_i)}{|V_i|e^{-j\delta_i}} + \sum_{n=p+1}^{p+q}|H_{tn}|e^{j\theta_{tn}}\left(|V_n|e^{j\delta_n} - |V_s|e^{j\delta_{sn}}\right)\right]$$

$$= \sum_{i=1}^{p}\left[\frac{|V_t||H_{ti}|}{|V_i|}P_i\,(cos(\delta_t - \theta_{ti} - \delta_i) - j\,sin(\delta_t - \theta_{ti} - \delta_i) - j\frac{|V_t||H_{ti}|}{|V_i|}Q_i(cos(\delta_t - \theta_{ti} - \delta_i) - j\,sin(\delta_t - \theta_{ti} - \delta_i)\right]$$

$$+ \sum_{n=p+1}^{p+q}[|V_t||H_{tn}||V_n|(\cos(\theta_{tn} + \delta_n - \delta_t) + j\,\sin(\theta_{tn} + \delta_n - \delta_t)) - |V_t||H_{tn}||V_s|(\cos(\theta_{tn} + \delta_s - \delta_t) + j\,\sin(\theta_{tn} + \delta_s - \delta_t))]$$

By separating real and reactive powers after comparing with the general form, the real and reactive powers are obtained

$$P_t = \sum_{i=1}^{p}\frac{1}{|V_i|}[|V_t||H_{ti}|P_i \cos(\delta_t - \theta_{ti} - \delta_i) - |V_t||H_{ti}|Q_i \sin(\delta_t - \theta_{ti} - \delta_i)] + \sum_{n=p+1}^{p+q}[|V_t||H_{tn}||V_n| \cos(\theta_{tn} + \delta_n - \delta_t) - |V_t||H_{tn}||V_s| \cos(\theta_{tn} + \delta_s - \delta_t)]$$

$$Q_t = \sum_{i=1}^{p}\frac{1}{|V_i|}[|V_t||H_{ti}|P_i \sin(\delta_t - \theta_{ti} - \delta_i) + |V_t||H_{ti}|Q_i \cos(\delta_t - \theta_{ti} - \delta_i)] + \sum_{n=p+1}^{p+q}[|V_t||H_{tn}||V_n| \sin(\theta_{tn} + \delta_n - \delta_t) - |V_t||H_{tn}||V_s| \sin(\theta_{tn} + \delta_s - \delta_t)]$$

4.0 GENERALIZED JACOBIAN COEFFICIENT MATRIX IN POLAR FORM

From the above real and reactive power equations the generalized hybrid Jacobian coefficient matrix is represented as follow

$$\begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_p \\ \vdots \\ \Delta P_{p+2} \\ \vdots \\ \Delta P_{p+q} \\ \vdots \\ \Delta Q_2 \\ \vdots \\ \Delta Q_p \\ \vdots \\ \Delta Q_{p+2} \\ \vdots \\ \Delta Q_{p+q} \end{bmatrix} = \begin{bmatrix}
\frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_p} & \frac{\partial P_2}{\partial \delta_{p+2}} & \cdots & \frac{\partial P_2}{\partial \delta_{p+q}} & \frac{\partial P_2}{\partial |V_2|} & \cdots & \frac{\partial P_2}{\partial |V_p|} & \frac{\partial P_2}{\partial |V_{p+2}|} & \cdots & \frac{\partial P_2}{\partial |V_{p+q}|} \\
\frac{\partial P_q}{\partial \delta_2} & \cdots & \frac{\partial P_q}{\partial \delta_p} & \frac{\partial P_q}{\partial \delta_{p+2}} & \cdots & \frac{\partial P_q}{\partial \delta_{p+q}} & \frac{\partial P_q}{\partial |V_2|} & \cdots & \frac{\partial P_q}{\partial |V_p|} & \frac{\partial P_q}{\partial |V_{p+2}|} & \cdots & \frac{\partial P_q}{\partial |V_{p+q}|} \\
\frac{\partial P_{p+2}}{\partial \delta_2} & \cdots & \frac{\partial P_{p+2}}{\partial \delta_p} & \frac{\partial P_{p+2}P_2}{\partial \delta_{p+2}} & \cdots & \frac{\partial P_{p+2}}{\partial \delta_{p+q}} & \frac{\partial P_{p+2}}{\partial |V_2|} & \cdots & \frac{\partial P_{p+2}}{\partial |V_p|} & \frac{\partial P_{p+2}}{\partial |V_{p+2}|} & \cdots & \frac{\partial P_{p+2}}{\partial |V_{p+q}|} \\
\frac{\partial P_{p+q}}{\partial \delta_2} & \cdots & \frac{\partial P_{p+q}}{\partial \delta_p} & \frac{\partial P_{p+q}}{\partial \delta_{p+2}} & \cdots & \frac{\partial P_{p+q}}{\partial \delta_{p+q}} & \frac{\partial P_{p+q}}{\partial |V_2|} & \cdots & \frac{\partial P_{p+q}}{\partial |V_p|} & \frac{\partial P_{p+q}}{\partial |V_{p+2}|} & \cdots & \frac{\partial P_{p+q}}{\partial |V_{p+q}|} \\
\frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_p} & \frac{\partial Q_2}{\partial \delta_{p+2}} & \cdots & \frac{\partial Q_2}{\partial \delta_{p+q}} & \frac{\partial Q_2}{\partial |V_2|} & \cdots & \frac{\partial Q_2}{\partial |V_p|} & \frac{\partial Q_2}{\partial |V_{p+2}|} & \cdots & \frac{\partial Q_2}{\partial |V_{p+q}|} \\
\frac{\partial Q_p}{\partial \delta_2} & \cdots & \frac{\partial Q_p}{\partial \delta_p} & \frac{\partial Q_p}{\partial \delta_{p+2}} & \cdots & \frac{\partial Q_p}{\partial \delta_{p+q}} & \frac{\partial Q_p}{\partial |V_2|} & \cdots & \frac{\partial Q_p}{\partial |V_p|} & \frac{\partial Q_p}{\partial |V_{p+2}|} & \cdots & \frac{\partial Q_p}{\partial |V_{p+q}|} \\
\frac{\partial Q_{p+2}}{\partial \delta_2} & \cdots & \frac{\partial Q_{p+2}}{\partial \delta_p} & \frac{\partial Q_{p+2}}{\partial \delta_{p+2}} & \cdots & \frac{\partial Q_{p+2}}{\partial \delta_{p+q}} & \frac{\partial Q_{p+2}}{\partial |V_2|} & \cdots & \frac{\partial Q_{p+2}}{\partial |V_p|} & \frac{\partial Q_{p+2}}{\partial |V_{p+2}|} & \cdots & \frac{\partial Q_{p+2}}{\partial |V_{p+q}|} \\
\frac{\partial Q_{p+q}}{\partial \delta_2} & \cdots & \frac{\partial Q_{p+q}}{\partial \delta_p} & \frac{\partial Q_{p+q}}{\partial \delta_{p+2}} & \cdots & \frac{\partial Q_{p+q}}{\partial \delta_{p+q}} & \frac{\partial Q_{p+q}}{\partial |V_2|} & \cdots & \frac{\partial Q_{p+q}}{\partial |V_p|} & \frac{\partial Q_{p+q}}{\partial |V_{p+2}|} & \cdots & \frac{\partial Q_{p+q}}{\partial |V_{p+q}|}
\end{bmatrix} \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_p \\ \vdots \\ \Delta\delta_{p+2} \\ \vdots \\ \Delta\delta_{p+q} \\ \vdots \\ \Delta|V_2| \\ \vdots \\ \Delta|V_p| \\ \vdots \\ \Delta|Vp+_2| \\ \vdots \\ \Delta|V_{p+q}| \end{bmatrix}$$

The following are the equations for the elements of the Jacobian coefficient matrix which is simply stated as

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix}$$

The diagonal and off-diagonal elements are calculated here by taking the reference from the hybrid Jacobian coefficient matrix which is mentioned in eqn. (12)

4.1 Generalized equations for diagonal and off-diagonal elements

The diagonal and off diagonal elements of each individual sub matrix are given as

Diagonal elements of J_1 : $\frac{\partial P_r}{\partial \delta_r} =$

$$\frac{1}{|H_{rr}|}\Big\{|V_r||V_s|\sin(\delta_r+\theta_{rr}-\delta_s) - \sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}[-|V_r||H_{ri}|P_i\sin(\delta_r+\theta_{rr}-\theta_{ri}-\delta_i) - |V_r||H_{ri}|Q_i\cos(\delta_r+\theta_{rr}-\theta_{ri}-\delta_i)] - \sum_{n=p+1}^{p+q}[-|V_r||H_{rn}||V_n|\sin(\theta_{rr}-\delta_n+\delta_r-\theta_{rn}) - |V_r||H_{rn}||V_s|\sin(\theta_{rr}-\delta_s+\delta_r-\theta_{rn})]\Big\}$$

$$\frac{\partial P_r}{\partial \delta_t} = 0$$

$$\frac{\partial P_t}{\partial \delta_r} = 0$$

$$\frac{\partial P_t}{\partial \delta_t} = \sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}[-|V_t||H_{ti}|P_i\sin(\delta_t-\theta_{ti}-\delta_i) - |V_t||H_{ti}|Q_i\cos(\delta_t-\theta_{ti}-\delta_i)] + \sum_{n=p+1}^{p+q}[|V_t||H_{tn}||V_n|\sin(\theta_{tn}+\delta_n-\delta_t) - |V_t||H_{tn}||V_s|\sin(\theta_{tr}+\delta_s-\delta_t)]$$

Off-diagonal elements of J1:

$$\frac{\partial P_r}{\partial \delta_i} = \frac{1}{|H_{rr}|}\Big\{-\frac{1}{|V_1|}[|V_r||H_{ri}|P_i\sin(\delta_r+\theta_{rr}-\theta_{ri}-\delta_i) + |V_r||H_{ri}|Q_i\cos(\delta_r+\theta_{rr}-\theta_{ri}-\delta_i)]\Big\}$$

$$\frac{\partial P_r}{\partial \delta_n} = \frac{1}{|H_{rr}|}\{|V_r||H_{rr}||V_n|P_i\sin(\delta_r+\theta_{rr}-\theta_{rn}-\delta_n)\}$$

$$\frac{\partial P_t}{\partial \delta_i} = \frac{1}{|V_i|}[|V_t||H_{ti}|P_i\sin(\delta_t-\theta_{ti}-\delta_i) + |V_t||H_{ti}|Q_i\cos(\delta_t-\theta_{ti}-\delta_i)]$$

$$\frac{\partial P_t}{\partial \delta_i} = [-|H_{tn}||V_t||V_n|\sin(\theta_{tn}+\delta_n-\delta_t)]$$

Diagonal elements of j_2*:*

$$\frac{\partial P_r}{\partial |V_r|} = \frac{1}{|H_{rr}|}\Big\{2|V_r|cos\theta_{rr} - |V_s|\cos(\delta_r+\theta_{rr}-\delta_s) - \sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}[|H_{ri}|P_i\cos(\delta_r-\theta_{rr}-\theta_{ri}-\delta_i) - |H_{ri}|Q_i\sin(\delta_r-\theta_{rr}-\theta_{ri}-\delta_i)] - \sum_{n=p+1}^{p+q}[|H_{rn}||V_n|\cos(\delta_r+\theta_{rr}-\theta_{rn}-\delta_n) - |H_{rn}||V_n|\cos(\delta_r+\theta_{rr}-\theta_{rn}-\delta_s)]\Big\}$$

$$\frac{\partial P_r}{\partial |V_t|} = 0 \qquad \frac{\partial P_t}{\partial |V_r|} = 0$$

$$\frac{\partial P_t}{\partial |V_t|} = \sum_{i=1}^{p}\frac{1}{|V_i|}[H_{ti}P_i\cos(\delta_t-\theta_{ti}-\delta_i) - |H_{ti}|Q_i\sin(\delta_t-\theta_{ti}-\delta_i)] + \sum_{n=p+1}^{p+q}[|H_{tn}||V_i|\cos(\theta_{tn}+\delta_n-\delta_t) - |H_{tn}||V_s|\cos(\theta_{tn}+\delta_n-\delta_t)]$$

Off diagonal elements of j_2:

$$\frac{\partial P_r}{\partial |V_i|} = \frac{1}{|H_{rr}|}\left\{\frac{1}{|V_i|}\left[|V_r||H_{ri}|P_i\cos(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i) - |V_r||H_{ri}|Q_i\sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)\right]\right\}$$

$$\frac{\partial P_r}{\partial |V_n|} = \{-[|V_r||H_{rn}|\cos(\delta_r + \theta_{rr} - \theta_{rn} - \delta_n)]\}$$

$$\frac{\partial P_t}{\partial V_i} = -\frac{1}{|V_i|^2}\{|V_t||H_{ti}||P_i|\cos(\delta_t - \theta_{ti} - \delta_i) - |V_t||H_{ti}|Q_i\sin(\delta_t - \theta_{ti} - \delta_i)\}$$

$$\frac{\partial P_t}{\partial |V_n|} = |V_t||H_{tn}|\cos(\delta_{tn} + \delta_n - \delta_t)$$

Diagonal elements of J_3: $\frac{\partial Q_r}{\partial|\delta_r|} =$

$$\frac{1}{|H_{rr}|}\left\{-|V_r||V_s|cos(\theta_{rr} + \delta_r - \delta_s) - \sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}\left[[|V_r||H_{ri}|P_i\cos(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i) - |V_r||H_{ri}|Q_i\sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)] - \sum_{n=p+1}^{p+q}[|V_r||H_{rn}||V_n|\cos(\delta_r + \theta_{rr} - \theta_{rn} - \delta_n) - |H_{rn}||V_r||V_s|\cos(\delta_r + \theta_{rr} - \theta_{rn} - \delta_s)]\right]\right\}$$

$$\frac{\partial Q_r}{\partial \delta_t} = 0 \qquad \frac{\partial Q_r}{\partial \delta_r} = 0$$

$$\frac{\partial Q_t}{\partial \delta_t} = \sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}\left[\frac{\partial Q_t}{\partial \delta_t}\cos(\delta_t - \theta_{ti} - \delta_i) - |V_t||H_{ti}|Q_i\sin(\delta_t - \theta_{ti} - \delta_i)\right] - \sum_{n=p+1}^{p+q}[|V_t||H_{tn}||V_n|\cos(\delta_n + \theta_{tn} - \delta_t) - |H_{tn}||V_t||V_s|\cos(\delta_s + \theta_{tn} - \delta_t)]$$

Off diagonal elements of j_3:

$$\frac{\partial Q_r}{\partial \delta_i} = \frac{1}{|H_{rr}|}\left\{-\frac{1}{|V_i|}\left[-|V_r||H_{ri}|P_i\cos(\delta_r + \theta_{rr} - \theta_{rn} - \delta_i) + |V_r||H_{ri}|Q_i\sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)\right]\right\}$$

$$\frac{\partial Q_r}{\partial \delta_i} = \frac{1}{|H_{rr}|}\{-[-|V_r||H_{rn}||V_n|\cos(\delta_r + \theta_{rr} - \theta_{rn} - \delta_n)]\}$$

$$\frac{\partial Q_t}{\partial \delta_i} = -\frac{1}{|V_i|}\{-|V_t||H_{ti}||P_i|\cos(\delta_t - \theta_{ti} - \delta_i) + |V_t||H_{ti}|Q_i\sin(\delta_t - \theta_{ti} - \delta_i)\}$$

$$\frac{\partial Q_t}{\partial \delta_n} = |V_t||H_{tn}||V_n|\cos(\delta_n + \theta_{tn} - \delta_t)$$

Diagonal elements of J_4: $\frac{\partial Q_r}{\partial|V_r|} =$

$$\frac{1}{|H_{rr}|}\left\{2|V_r|\sin\theta_{rr}) - |V_s|\sin(\delta_r + \theta_{rr} - \delta_s) - \sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}\left[[|H_{ri}|P_i\sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i) + |H_{ri}|Q_i\cos(\delta_r + \theta_{rr} - \theta_{rn} - \delta_i)] - \sum_{n=p+1}^{p+q}[|H_{rn}||V_n|\sin(\delta_r + \theta_{rr} - \theta_{rn} - \delta_n) - |H_{rn}||V_s|\sin(\delta_r + \theta_{rr} - \theta_{rn} - \delta_s)]\right]\right\}$$

$$\frac{\partial Q_r}{\partial |V_t|} = 0 \qquad \frac{\partial Q_t}{\partial |V_r|} = 0$$

$$\frac{\partial Q_r}{\partial |V_t|} = \left\{\sum_{\substack{i=1\\ i\neq r}}^{p}\frac{1}{|V_i|}[|H_{ti}|P_i\sin(\delta_t - \theta_{ti} - \delta_i) + |H_{ti}|Q_i\cos(\delta_t - \theta_{ti} - \delta_i)] - \sum_{n=p+1}^{p+q}[|H_{tn}||V_s|\sin(\theta_{tn} + \delta_n - \delta_t) - |H_{tn}||V_s|\sin(-\delta_t + \theta_{tn} + \delta_s)]\right\}$$

Off diagonal elements of j_7:

$$\frac{\partial Q_r}{\partial |V_i|} = \frac{1}{|H_{rr}|}\left\{\frac{1}{|V_i|^2}\left[|V_r||H_{ri}|P_i\sin(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i) + |V_r||H_{ri}|Q_i\cos(\delta_r + \theta_{rr} - \theta_{ri} - \delta_i)\right]\right\}$$

$$\frac{\partial Q_r}{\partial |V_n|} = \frac{1}{|H_{rr}|}\{[|V_r||H_{rn}|\sin(\delta_r + \theta_{rr} - \theta_{rn} - \delta_n)]\}$$

$$\frac{\partial Q_t}{\partial |V_i|} = -\frac{1}{|V_i|^2}\{|V_t||H_{ti}||P_i| \sin(\delta_t - \theta_{ti} - \delta_i) + |V_t||H_{ti}|Q_i \cos(\delta_t - \theta_{ti} - \delta_i)\}$$

$$\frac{\partial Q_t}{\partial |V_n|} = \sum_{n=p+1}^{p+q} |H_{tn}||V_t| \sin(\theta_{tn} + \delta_n - \delta_t$$

5.0 NUMERICAL EXAMPLE

The proposed algorithm was tested for IEEE 30 bus, 103 bus and 140 bus Indian utility systems. The power flow solution was carried out with i3 processor computer. The operating time and number of iterations with optimal combination of buses of the test systems are tabulated in Table 1.

TABLE 1

SUMMARY OF EXISTING AND PROPOSED METHODS

Test System	Number of buses in Y-form	Number of buses in Z- form	Computation time (Sec)		Number of iterations	
			Existing method [19]	Proposed method	Existing method [19]	Proposed method
IEEE30 bus	30	---	---	17.59	---	3
	11	19	---	10.14	---	2
103 bus	103	---	24.25	17.01	5	4
	33	70	18.18	14.25	4	2
140 bus	140	---	30.32	25.50	6	5
	57	83	22.40	19.23	4	3

TABLE 2

REAL AND REACTIVE POWER LOSS VARIATIONS OF IEEE 30 BUS SYSTEM

Line number	Real power loss		Reactive power loss	
	Existing method	Proposed method	Existing method	Proposed method
1	0.594272	0.2782	-4.06953	-4.7315
2	0.696107	0.3368	-1.59394	-2.8967
3	0.533361	0.28	-2.29725	-2.924
4	0.182906	0.084	-0.35503	-0.6163
5	0.92171	0.7994	-0.54199	-0.9391
6	0.836445	0.4852	-1.43573	-2.3753
6	0.139856	0.1256	-0.44623	-0.4788
7	0.005916	0.0381	-2.05746	-1.9667
8	0.143941	0.1934	-1.29591	-1.1261
9	0.033176	0.0128	-0.80779	-0.8693
10	-5.3E-15	0	0.411234	2.6018
11	3.55E-15	0	0.63727	0.3715
12	0	0	1.108924	5.6849
13	0	0	1.099743	1.1642
14	7.11E-15	0	1.857419	1.0897
15	0	0	0.559177	2.2795
16	0.07682	0.0882	0.159694	0.1834
17	0.231062	0.2836	0.455142	0.5587
18	0.058187	0.0948	0.122346	0.1993
19	0.007042	0.0097	0.006363	0.0088
20	0.013964	0.0347	0.032589	0.0809
21	0.040627	0.0616	0.082731	0.1259
22	0.005494	0.0117	0.011108	0.0236
23	0.016177	0.0154	0.032354	0.0308
24	0.077968	0.0763	0.174094	0.1704
25	0.013171	0.0178	0.034351	0.0463
26	0.114051	0.1001	0.245472	0.2154
27	0.054694	0.0441	0.112773	0.091
28	0.000537	0.0029	0.001093	0.0059
29	0.037674	0.0448	0.076101	0.0904
30	0.05389	0.03	0.083881	0.0467
31	0.009415	0.0232	0.019259	0.0474
32	0.001905	0.0687	0.003327	0.1201
33	0.044326	0.0464	0.06621	0.0693
34	0.012153	0.0971	0.023205	0.1855
35	-3.6E-15	0	1.092415	1.7299
36	0.085577	0.0867	0.161693	0.1637
37	0.160943	0.163	0.302936	0.3068
38	0.033283	0.0337	0.06289	0.0637
39	0.006311	0.0071	-4.36399	-4.2887
40	0.035028	0.0519	-13.2753	-1.1312
41	0.594272	0.2782	-4.06953	-4.7315

Existing method: NR rectangular form with hybrid bus Proposed method: NR polar form with hybrid bus

From the Table 1 it is observed that proposed NR method in polar form with hybrid bus gives the best results compared to existing methods in terms of the computation time and number of iterations.

And also observed from this proposed method the storage requirement is slightly less compared to existing methods. That shows the superiority of the proposed method. The real power and reactive power losses for existing and proposed methods of IEEE 30 bus system is given in Table 2. From this table it is observed that in proposed method real power losses are less compared to existing methods by 21.80%.

Voltage magnitude variation in different buses, variations of power flows and real and reactive power losses in each line of IEEE 30 bus system are shown in Figures. 1-4.

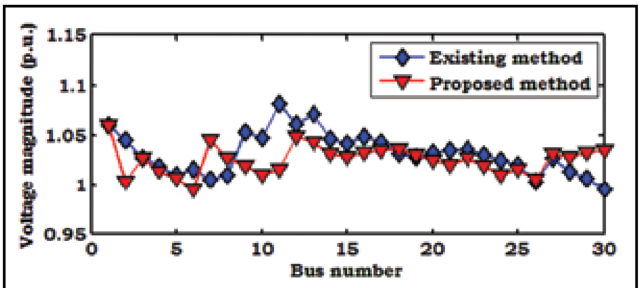

FIG.1 VARIATION OF VOLTAGE MAGNITUDE OF IEEE 30 BUS SYSTEM

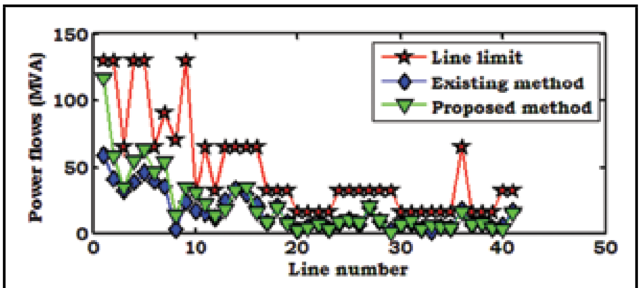

FIG.2 VARIATION OF POWER FLOWS OF IEEE 30 BUS SYSTEM

From Figure 1 it is observed that the maximum voltage magnitude variations are observed in buses 10 and 11 when compared to remaining buses. From Figure 2

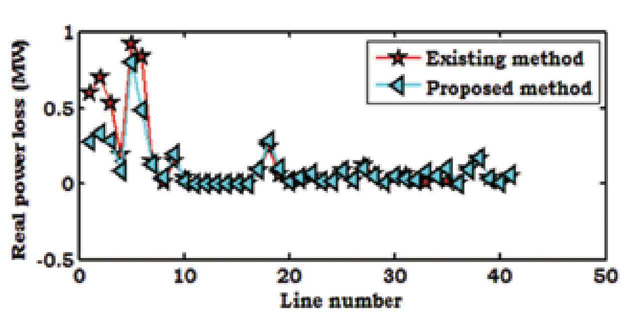

FIG.3 VARIATION OF REAL POWER LOSS OF IEEE 30 BUS SYSTEM

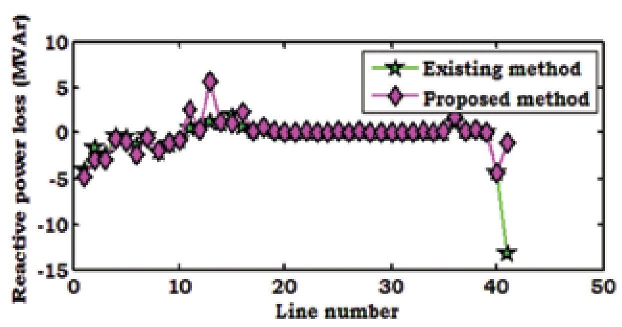

FIG.4 VARIATION OF REACTIVE POWER LOSS

it is observed that in proposed method maximum number of the lines carry the more power when compared to existing method. From Figure 3 it is observed that maximum real power loss variations are observed in lines 1to 3 when compared to other lines. From Figure 4 it is observed that maximum reactive power losses are observed in lines 11, 13 and 41.

6.0 CONCLUSIONS

This paper presents a method of forming simple NR power flow equation in polar form using the hybrid bus. The algorithm is well suited to compute the application of large power network problems and requires considerably less storage. Using proposed NR algorithm with hybrid bus for load flow studies ensures the faster convergence in iterative solutions. Hence, the computation time is less for the proposed method in comparison with the existing method. Finally, from the analysis, it has been concluded that proposed method yields better results compared to existing methods. The proposed methodology has been tested on standard test systems IEEE-30 bus, 103bus and 140bus Indian utility systems with supporting numerical results.

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