A Fast and Reliable Quadratic Approach for Q-adjustments in Fast Decoupled Load Flow Model

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***Abstract*—The paper presents a new fast, reliable and relatively simple decoupled Quadratic Load Flow(DQLF) algorithm for Q-adjustments in power flow solutions. Q-adjusted solutions are inevitable for reactive power planning and management studies. For solving power flow problems, the Fast Decoupled Load Flow(FDLF) is probably the most popular, because of its efficiency. But for Q-adjusted studies, the matrix updating problem associated with B'' matrix remains unresolved. Refactorization of B'' matrix demands more CPU time. The proposed approach eliminates formation and refactorization of B'' matrix, for both well behaved and ill-conditioned systems of Q-unadjusted and adjusted cases. The new method minimizes the computational burden by solving for the busbar voltage magnitudes (V) using a non-linear quadratic equation and it reduces the execution time significantly. The solution of this non-linear equation undoubtedly offers better solution than that of a linear version. Improved and reliable convergence on normal and ill-conditioned system is expected. Enforcement of Q-limits is also very simple and effective. The proposed algorithm also proved to handle large degrees of ill-conditioning in Q-adjusted studies compared to the standard FDLF model. The performance of the proposed model is investigated by a number of case studies on IEEE test systems (14, 30, 57 & 118 bus) and results are reported for IEEE 118 bus system. The results indicate the established better convergence and reliability of the proposed model. It is atleast 50% faster than the traditional FDLF model for Q-adjusted case studies.**

***Index Terms*---- Fast Decoupled load Flow (FDLF), Decoupled Quadratic Load Flow (DQLF), ill-condition, r-factor**

I. INTRODUCTION

Load Flow solution is an iterative procedure to solve a set of simultaneous non-linear equations . Y-bus based algorithms for load flow studies are widely used in power system studies. The bus admittance matrix is highly sparse, and "Sparsity technique", which stores and operates only on non-zero elements of Y-bus would reduce both storage and execution time requirements of load flow drastically. A number of iterative techniques like Gauss Siedel, Newton Raphson (NR) load flow are proposed. NR load flow exhibits quadratic convergence, but requires more computer memory and execution time. The Fast Decoupled Load Flow(FDLF) model [1] requires less computer memory and reduced execution time than NR model. It uses two coupling submatrices as shown below.

$$[B'][\Delta\delta] = [\Delta P/V] \quad (1)$$

$$[B''][\Delta V] = [\Delta Q/V] \quad (2)$$

Where B', B'' are coupling sub matrices
$\Delta\delta$, correction vector for busbar angles
ΔV, correction vector for busbar voltages
ΔP, Active power mismatch vector
ΔQ, Reactive power mismatch vector

In the above final model, Stott and Alsac have made certain assumptions in forming B'-matrix. Parameters such as line series resistances, shunt reactances and off-nominal transformer taps are ignored. Van Amerongen [2] had proposed a BX scheme for the FDLF model, where line resistances are considered in the formation of [B'] and are omitted in the formation of [B'']. This scheme is claimed to exhibit a better convergence property than that of the Stott FDLF model particularly for various degrees of ill-conditioning.

The good convergence property of the BX model can be attributed mainly to the absence of resistances when [B''] is formed. It is recommended that [3] for all practical purposes, the FDLF based on BX model can provide more or less best convergence property for both well behaved and ill-conditioned systems.

The coupling sub matrices are fixed as long as there is no change in the system topology or the status of the regulated buses. Both matrices must be updated when there is a change in system topology (line outages). Even under normal operating condition, the change in the status of regulated bus affects the second matrix.

FDLF with refactorization technique is proved to be very rigorous for Q-limit enforcement at PV buses. But this approach takes more CPU time. Then partial refactorization techniques are applied to reduce CPU time. But the Partial Refactorization method is efficient only if there are a few buses, which change their status. The efficiency of partial refactorization method is inversely proportional to number of bus status changes. The above discussion illustrates that updating B" remains unresolved. Therefore an alternative method of solution of LF is needed.

A hybrid model is proposed in [4] which uses nodal iterative model derived from power injection equations , which does not have matrix updating problem, but cannot be used because of its slow convergence. The next step, a hybrid model was created by combining the active network of the FDLF[1] with the reactive network of the nodal iterative model. The resultant model, which is the hybrid version of FDLF [4]. The results reported in ref [4] need to be verified. With $Q_{specified}$ injection in the proposed iterative approach, the algorithm never converges with characteristics reported in [4] for Q-adjusted or unadjusted studies. A Robust Fast decoupled model is proposed in [5] which works well for Q-unadjusted studies, but shows poor convergence for Q-adjusted studies.

II. PROPOSED MODEL

In this model the phase angle corrections $\Delta\delta$ are obtained from BX- model based equation

$$[B'][\Delta\delta] = [\Delta P/V]$$

where $B'_{pq} = -B_{pq}$, $B'_{pp} = -\sum_{q \in \text{ц}p} (B_{pq})$

цp = adjacent buses of p^{th} bus, $B'_{pp} = 10^{20}$ for p=slack bus

For the bus voltage magnitudes the following new quadratic approach is employed. The active and reactive power injections at p^{th} bus are given by:

$$P_p = \sum_{q=1}^{n} V_P V_q Y_{pq} \cos(\delta_{pq} - \theta_{pq}) \quad (3)$$

$$Q_p = \sum_{q=1}^{n} V_P V_q Y_{pq} \sin(\delta_{pq} - \theta_{pq}) \quad (4)$$

Where P_P, Q_p are active and reactive power injections at p^{th} bus

n is the number of buses in the system

V_p, V_q are magnitudes of voltages at p^{th}, q^{th} bus respectively

$\delta_{pq} = \delta_p - \delta_q$,where δ_p, δ_q are angles of voltages E_p and E_q.

E_p, E_q are complex voltages of p and q buses.

Now add (3) and (4) and resulting equation is :

$$P_p + Q_p = \sum_{q=1, \neq p}^{n} V_P V q Y pq \cos(\delta_{pq} - \theta_{pq}) + \sum_{q=1, \neq p}^{n} V_P V_q Y_{pq} \sin(\delta_{pq} - \theta_{pq}) + V_p^2 (G_{pp} - B_{pp})$$

which can be written as

$$A V_p^2 + B V_P + C = 0 \quad (5)$$

Where

$A = (G_{pp} - B_{pp})$

$$B = \sum_{q=1, \neq p}^{n} V_q Y_{pq} \cos(\delta_{pq} - \theta_{pq}) + \sum_{q=1, \neq p}^{n} V_q Y_{pq} \sin(\delta_{pq} - \theta_{pq})$$

$C = -(P_p + Q_p)$

P_p, Q_p are scheduled power injections at pth bus at a given loading level.

$P_p = P_{gen} - P_{load}$
$Q_p = Q_{gen} - Q_{load}$

Equation (5) is a quadratic equation in V_p. The solution of this non-linear equation undoubtedly offers better solution than that of a linear version. Improved and reliable convergence on normal and ill-conditioned system is expected. Enforcement of Q-limits is also very simple and effective. Equation (5) will have two distinct roots. The more realistic value for system voltage is obtained using $(-B + \text{sqrt}(B^2 - 4AC))/2A$.

The following set of equations are solved for the proposed Decoupled Quadratic Load flow (DQLF) model.

$[B'][\Delta\delta] = [\Delta P/V]$ from BX or XB FDLF model. (6)

$$A V_p^2 + B V_P + C = 0 \quad (7)$$

III. TEST RESULTS

In this section test results are reported to demonstrate the advantages of the proposed DQLF model over conventional FDLF models for normal cases and for cases with high R/X ratios. The ill-conditioning is simulated by multiplying all branch resistances by a positive scale factor and degree of ill conditioning is varied by varying its value.

The DQLF can be iterated using (1δ1V) scheme or (1δ2V) scheme. In 1δ1V scheme (6) is solved for $\Delta\delta$ and complex voltages are computed. Using these voltages (7) is solved for voltage magnitudes and complex bus voltages are recomputed. In 1δ2V scheme voltage magnitude half iteration is repeated twice before it goes to phase angle corrections. An acceleration factor is added in voltage half iteration to speed up the convergence.

TABLE 1 shows the iteration counts and execution times for FDLF XB, BX models and DQLF model for unadjusted case studies. The results clearly show that for normal case and for various r-scale factors, the DQLF model's performance is as good as the conventional FDLF models.

TABLE 2 shows the iteration counts and execution times for FDLF XB, BX models and DQLF for adjusted case studies. The results clearly show that , the proposed DQLF model converges almost 50% faster than conventional FDLF models. Even though the number of iterations are slightly more than the conventional FDLF models, faster execution of the DQLF model can be attributed to the elimination of formation and refactorization of second constant slope matrix. In Adjusted case studies, the B" matrix has to be refactorized whenever a generator bus changes its status. Therefore the proposed approach which calculates the voltage magnitudes at all load buses (including the buses which are switched from PV to PQ) using a quadratic equation, offers faster execution specially when more number of generator buses are present in the given system.

TABLE.1 Iterations counts and execution time in milliseconds for several r-scale factors (tolerance 0.0001 pu) for IEEE 118 bus system (Gen Q-limits not considered (unadjusted)); Acceleration factor (alpha)=1.38

r-scale factor	FDLF XB	DQLF 1δ2V XB	FDLF BX	DQLF 1δ2V BX	FDLF XB Time in ms	DQLF 1δ2V XB Time in ms	FDLF BX Time in ms	DQLF 1δ2V BX Time in ms
1.0	4.5	8.5	4.5	7.5	40	40	40	38
2.0	10.5	10.5	5.0	8.5	50	42	40	40
3.0	19.5	19.5	6.5	8.5	60	50	42	40
3.5	27.5	27.5	9.0	9.5	70	60	45	42
4.0	43.5	44.5	15	13.5	90	80	50	50
5.0	nc	nc	nc	nc				

TABLE 2. Iterations counts and execution time in milliseconds for several r-scale factors (tolerance 0.0001 pu) for IEEE 118 bus system(Gen Q-limits considered (adjusted)); acceleration factor(Alpha) = 1.38

r-scale factor	FDLF XB	DQLF 1δ2V XB	FDLF BX	DQLF 1δ2V BX	FDLF XB Time in ms	DQLF 1δ2V XB Time in ms	FDLF BX Time in ms	DQLF 1δ2V BX Time in ms
1.0	4.5	9.5	4.5	9.5	90	44	90	44
2.0	10.5	10.5	5.5	9.5	190	50	100	44
2.5	14.5	14.5	6.5	9.5	260	50	120	44
3.0	nc	22.5	nc	10.5		60		50
3.5	nc	37.5		14.5		80		60
4.0	nc	nc		nc		nc		nc

nc=more than 60iterations

Fig.1a to 4b show the convergence characteristics of IEEE 118 bus system for all the above discussed models for adjusted case studies. Fig.1a, 1b show the convergence characteristic of FDLF BX model for normal case and with r-factor 2.5 respectively. Fig.2a, 2b show the convergence characteristics of FDLF XB model for normal case and with r-factor 2.5 respectively. For ill-conditioned system, the XB scheme shows slow convergence. DELQMAX undergoes severe oscillations.

Fig.3a, 3b show the convergence characteristics of BX adjusted DQLF model for normal case and with r-factor 2.5 respectively. Fig.4a, 4b show the convergence characteristics of XB adjusted DQLF model for nomal case and with r-factor 2.5 respectively. Both the models show considerably faster convergence than FDLF models. The most obvious conclusion that can be drawn from these figures is that, the active power mismatches and the reactive power mismatches exhibit equal rate of convergence without causing violent oscillations. This helps in offering a reliable solution even under high degree of ill-conditioning.

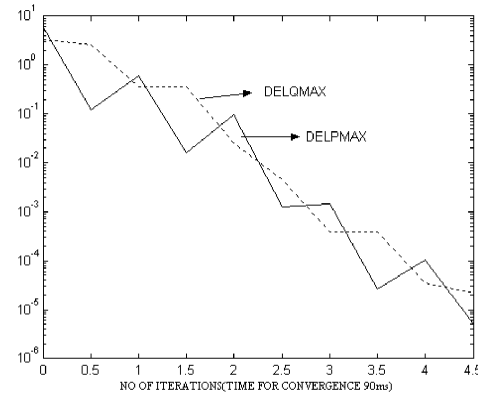

figure 1a. FDLF BX model r-factor=1.0

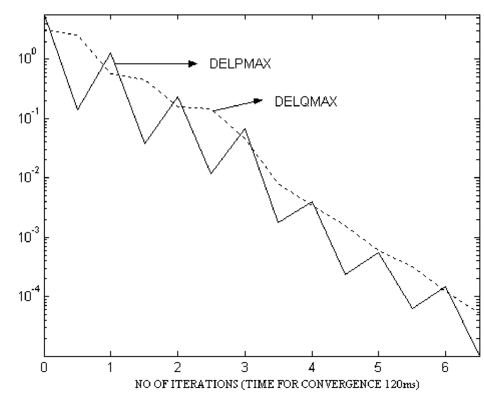

figure1b. FDLF BX model r-factor=2.5

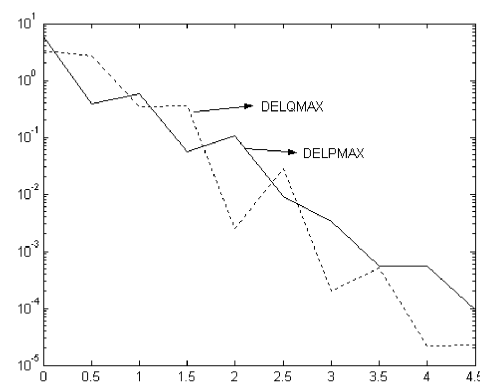

figure 2a.FDLF XB model r-factor=1.0

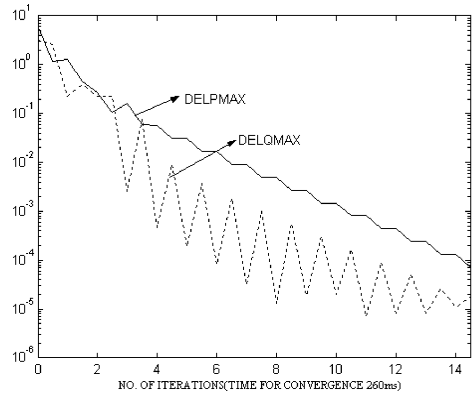

figure 2b.FDLF XB model r-factor=2.5

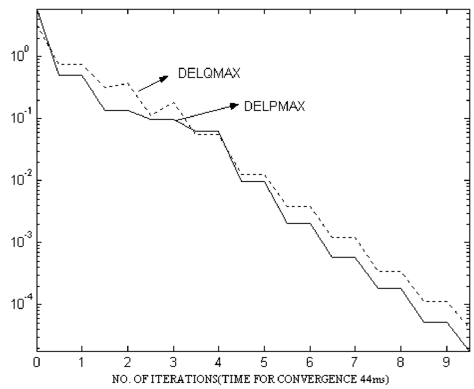

figure. 3a. BX DQLF model r-factor=1.0

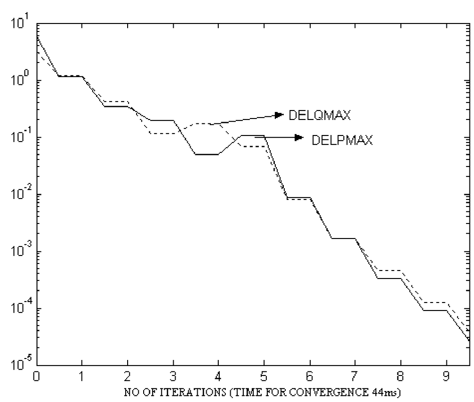

figure.3b.BX DQLF model r-factor=2.5

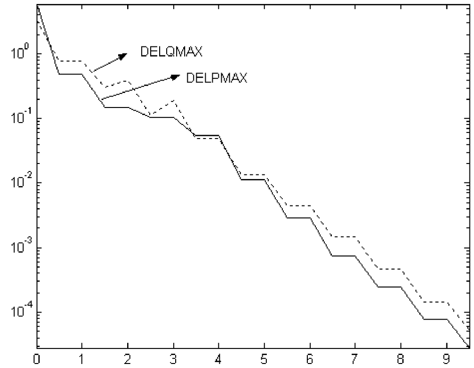

fig. 4a. XB DQLF model r-factor=1.0

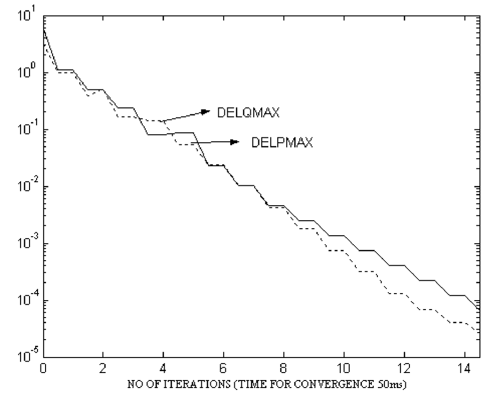

figure 4b.XB DQLF model r-factor=2.5

From test results following can be summarized :

When generator Q-limits are not considered

1. For small r-scale factors the proposed algorithm is as fast as the conventional FDLF .
2. For higher r-scale factors the number of iterations to converge are less.
3. 1δ2V approach performs much better than 1δ1V approach, both in terms of no. of iterations and execution times.
4. The decoupled quad model using BX model converges faster than that with XB model.

When generator Q-limits are considered

1. The proposed DQLF model is proved to be atleast 50% faster than conventional FDLF model.
2. For higher scale factors the DQLF model's performance is much better.
3. The proposed algorithm works well for large degrees of ill-conditioning.
4. 1δ2V approach performs better than 1δ1V, both interms of no. of iterations and execution times.

IV. CONCLUSIONS

The proposed Decoupled Quad model is atleast 50% faster than the traditional FDLF models for Q-adjusted case studies. It eliminates the formation and refactorization of B" matrix whenever a generator bus changes its status. Therefore considerable saving in the execution time has been achieved. Enforcement of Q-limits is very simple and effective. The proposed model exhibits very reliable convergence even for high degree of ill-conditioning , where traditional FDLF models failed to converge. The model will be very useful for reactive power planning and management studies on all sizes of system with any degree of ill-conditioning.

V. REFERENCES

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VI. BIOGRAPHIES

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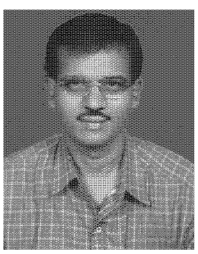

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