Chapter 2

Current Injection Based Power Flow

This chapter reports an improvement in the current injection based Newton-Raphson (CINR) load flow using a new representation of PV bus. This improved CINR is named as Mod-CINR. In Mod-CINR, representation of PV buses is same as CINR but modified equations are used to calculate current mismatch. Due to new equations, the convergence property of Mod-CINR is improved. Experimental tests have been performed on different IEEE standard bus systems and some practical unbalanced three-phase distribution systems and results of Mod-CINR are compared with different Newton-Raphson load flow techniques viz. Conventional Newton-Raphson(CNR) and CINR. The comparative analysis shows that the convergence property of Mod-CINR improves without increasing the number of equations.

2.1 Introduction

Power flow tools are extensively applied in power systems planning and operation. These are also used to provide initial conditions for several power system studies such as short-circuit, angle and voltage stability [18–20]. In real time operations, these are used for simulating transmission line contingencies and for determining load margin which require high computational processing time. Thus, there is a continuing search for methods that can provide faster convergence and are also more robust and reliable. Among various numerical methods used for solving power flow problems, "power injection" Newton-Raphson iterative method is the most widely used one, since it is more reliable and the required number of iterations are independent of size of the power system under consideration. Both, "power injection" and "current injection" power flow formulations can be written with voltages and admittances in either polar or rectangular coordinates. Some methods also use hybrid formulations [20].

Electric power distribution systems are characterized by high R/X ratio and unbalanced operation. These characteristics impose serious challenges for the development of efficient computational power flow techniques. Two basic approaches have been used to deal with this problem: (i) Newton and Newton like methods [21–23] and (ii) load flow for radial networks [24–27].

In [21] the network radial structure is explored to express the Jacobian matrix as a product of UDU^t, where U is a constant triangular matrix and D is a diagonal matrix, the elements of which are updated at every iteration. This method is developed for balanced networks.

In [22] the power flow equations for balanced networks are developed as a function consisting of new variables in place of V_i^2, $V_iV_jsin\theta_{ij}$ and $V_iV_jcos\theta_{ij}$ terms. The resulting system of equations are of the order of $3n$ (n=number of buses).

A three-phase power flow formulation (for unbalanced networks) is developed in [23] where the Jacobian matrix is presented in complex form, but some simplifications are introduced by neglecting the components of the mismatch arising due to voltage changes.

A compensation based technique is proposed in [24] for weakly meshed balance networks. In its first step, radial part of the network is solved using well known forward/backward sweep technique and in its second step, meshes are handled using nodal current injection based compensation. In [26] an improved version of this method has been presented, in which the branch power flows are used instead of the branch currents.

In [25], a Z_{bus} based approach is presented, in which the voltages at each bus depend on two factors viz. (i) the specified voltage sources (PV buses), and (ii) the equivalent current (PQ buses). In [27] further extensions of the methods of [25] and [26] are proposed for unbalanced loads.

In [28,29], the power flow formulations based on current injection mismatches (CINR) were proposed to resolve the issues of (i) large calculations involved in the update of Jacobian matrix in each iteration of CNR power flow and (ii) slow convergence in case of ill-conditioned systems . In CINR approach, each update of Jacobian matrix is faster than that in CNR power flow. This is so because, in CINR, only diagonal elements need to be evaluated in each update (iteration) of Jacobian matrix. Moreover, this formulation (CINR) does not require calculation of transcendental (sine and cosine) functions at all during calculation iterations.

The CINR method performs very well in case of systems having only PQ buses, but, in the case of presence of PV buses, the CINR mostly fails to converge. In order to address the problem of convergence in the presence of PV buses, many revised formulations of CINR (Rev-CINR) have been proposed [30,31]. In [30,31], PV buses are treated as PQ buses considering reactive power as an additional system variable. Consequently, this improvement increases the number of required equations to three for each of the PV buses [32]. The revisions discussed above do not make CINR a reliable method for transmission systems because these systems consist of many PV buses resulting in more number of additional variables as compared to the distribution systems which normally have relatively small number of PV buses. Hence, CINR is mostly used for distribution systems [33,34].

Current injection based power flow method proposed in [35] attempts to solve an augmented system of equations where bus voltages and current injections appear as state variables. The resulting simultaneous equations of power and current mismatches are solved using the Newton's method instead of combining nodal equations and the bus constraints into a single set of simultaneous nonlinear equations.

The current equations in the above-mentioned papers are expressed in rectangular coordinates or in a mix of polar and rectangular coordinates. Nevertheless, a variety of tools based on polar coordinates have been widely applied for power system analysis, such as power system dynamics analysis and state estimation. The use of rectangular coordinates results in a reduction of the effort to compute the Jacobian terms, since most of them remain constant during the iterative process. On the other hand, the use of polar coordinates leads to a smaller number of equations [35]. In most of the current injection formulations, the appropriate representation of PV buses has been the main concern. In case of PV bus, only one quantity (reactive power mismatch, $\triangle Q$) is unknown in polar formulation, contrary to the rectangular formulation, where two quantities (real and imaginary current mismatches) are unknown. Therefore, additional equations (one equation for each of the PV buses) need to be introduced in the rectangular formulation.

In [36] a hybrid polar coordinate formulation of current injection method is proposed using a dependent variable, $\triangle Q$, for each PV bus associated to an active power mismatch equation. A hybrid power flow method (NR-CINR) is presented in [37–39]where (i) PV buses are represented by equations of active power mismatches in terms of angle deviation, and (ii) PQ buses are represented by equations of current injection in rectangular coordinates.

A simplified Newton Raphson (NR) power flow method is presented in [40] where nonlinear current mismatch equations are expressed in polar coordinates. In [40], a comparison of above method has also been performed with other power flow methods having power mismatches in polar coordinates. The reactive powers at PV buses are kept constant during an iteration and is updated in the end of each of the iterations.

From the above discussion, it can be concluded that attempts have been made in literature to incorporate PV modelling in CIM. Nevertheless, CIM without incorporating PV modelling have got wide application in the conventional distribution system because of following two reasons. First, the conventional distribution systems don't have PV buses and second, CIM is more efficient and effective as compared to the conventional NR load flow methods for distribution systems. Nowadays, many types of sources are getting introduced in the distribution systems which need to be modelled as PV buses. Hence, there is need for such CIM methods which can effectively model and incorporate sources as PV buses.

In order to address this requirement, in this chapter a new method, Mod-CINR, has been proposed to model PV buses in CIM framework.

The main contributions of this chapter are as follows. Mod-CINR is more robust than other CINR based algorithm because it can solve a wide variety of power flow problems including systems having a large number of PV buses. Mod-CINR is more efficient than the other algorithms CNR, CINR, Rev-CINR, and NR-CINR except for FDBX. However, FDBX cannot be employed in distribution systems due to large R/X ratio, while Mod-CINR provides better convergence speed as compared to CNR. Hence, Mod-CINR is a better alternative for CNR in terms of efficiency. In Mod-CINR, PV buses are quiet better handled as compared to other representative algorithms because of the use of proposed equations for elements of the Jacobian matrix associated with PV buses.

Following parts of this chapter are organized as follows. Section 2.2 first presents basics of three-phase CIM for power flow discussing modelling of PQ buses and then discusses the incorporation of proposed PV bus modeling. Section 2.3 presents results of Mod-CINR (CINR incorporating proposed PV model) and its comparison with other CINR methods incorporating existing PV modeling approaches.

2.2 Three-Phase Current Injection Power flow

Before discussing the proposed PV modelling, three-phase CIM for power flow has been described in the following section for PQ buses.

2.2.1 Modelling of PQ buses

Total injected power at PQ bus i is given by

$$S_i^{sp} = P_i^{sp} + jQ_i^{sp} = E_i I_i^* \tag{2.1}$$

where

$$P_i^{sp} = P_{Gi}^{sp} - P_{Li}^{sp}, \tag{2.2}$$

$$Q_i^{sp} = Q_{Gi}^{sp} - Q_{Li}^{sp}, \text{ and} \tag{2.3}$$

$$E_i = V_{ri} + jV_{mi}. \tag{2.4}$$

Total injected current at PQ bus i can be derived from equation 2.1. From equation 2.1 we can define.

$$I_i = \frac{P_i^{sp} - jQ_i^{sp}}{E_i^*} \tag{2.5}$$

By converting equation 2.5 into its real and imaginary components, we get,

$$I_{ri} = \frac{P_i V_{ri} + Q_i V_{mi}}{V_i^2}, \text{ and} \tag{2.6}$$

$$I_{mi} = \frac{P_i V_{mi} - Q_i V_{ri}}{V_i^2}. \tag{2.7}$$

Current mismatch at PQ bus i in terms of power mismatch is derived by partial differentiation of equations 2.6 and 2.7 with respect to active and reactive powers as follows.

$$\triangle I_{ri} = \frac{\triangle P_i V_{ri} + \triangle Q_i V_{mi}}{V_i^2} \tag{2.8}$$

$$\triangle I_{mi} = \frac{\triangle P_i V_{mi} - \triangle Q_i V_{ri}}{V_i^2} \tag{2.9}$$

Power mismatches $\triangle P_i$ and $\triangle Q_i$ for bus i (PQ bus) are calculated in the same way as these are calculated in conventional Newton-Raphson (CNR) power flow, in the following manner.

$$\triangle P_i = P_i^{sp} - V_{ri} I_{ri}^{calc} - V_{mi} I_{mi}^{calc}, \text{ and} \tag{2.10}$$

$$\triangle Q_i = Q_i^{sp} - V_{mi} I_{ri}^{calc} + V_{ri} I_{mi}^{calc}. \tag{2.11}$$

Solution of non-linear equations 2.8 and 2.9 using Newton-Raphson numerical technique, considering all system buses as PQ type, can be given as follows.

$$\left[\begin{array}{c} \triangle I_{m1} \\ \triangle I_{r1} \\ \hline \triangle I_{m2} \\ \triangle I_{r2} \\ \hline :: \\ :: \\ \hline \triangle I_{mn} \\ \triangle I_{rn} \end{array}\right] = \left[\begin{array}{c|c|c|c} Y_{11}^* & Y_{12}^* & :: & Y_{1n}^* \\ \hline Y_{21}^* & Y_{22}^* & :: & Y_{23}^* \\ \hline :: & :: & :: & :: \\ \hline Y_{n1}^* & Y_{n2}^* & :: & Y_{nn}^* \end{array}\right] \left[\begin{array}{c} \triangle V_{r1} \\ \triangle V_{m1} \\ \hline \triangle V_{r2} \\ \triangle V_{m2} \\ \hline :: \\ :: \\ \hline \triangle V_{rn} \\ \triangle V_{mn} \end{array}\right] \tag{2.12}$$

where,

$$Y_{kk}^* = \begin{bmatrix} B'_{kk} & G'_{kk} \\ G''_{kk} & B''_{kk} \end{bmatrix}, \tag{2.13}$$

$$Y_{jk}^* = \begin{bmatrix} B_{jk} & G_{jk} \\ G_{jk} & -B_{jk} \end{bmatrix}, \tag{2.14}$$

$$B'_{kk} = B_{kk} - a_k, \tag{2.15}$$

$$G'_{kk} = G_{kk} - b_k, \tag{2.16}$$

$$G''_{kk} = G_{kk} - c_k, \text{ and} \tag{2.17}$$

$$B''_{kk} = -B_{kk} - d_k. \tag{2.18}$$

Here,

$$a_k = \frac{Q_k(V_{rk}^2 - V_{mk}^2) - 2V_{rk}V_{mk}P_k}{V_k^4},$$

$$b_k = \frac{P_k(V_{rk}^2 - V_{mk}^2) + 2V_{rk}V_{mk}Q_k}{V_k^4},$$

$$c_k = -b_k, \text{ and}$$

$$d_k = a_k.$$

So far, incorporation of PQ buses in CIM formulation has been discussed. Now in the following section, proposed PV modeling used in Mod-CIM formulation has been described.

2.2.2 Modelling of PV buses for balanced cases

For CINR, different PV bus models are proposed in [28–30] to handle the PV buses in distribution systems. However, their convergence performance degrades when distribution systems consist of high number of PV buses w.r.t. number of system buses. This is because the expressions of elements of the Jacobian matrix do not model PV buses properly rather they proceed to solve systems with PV buses retaining PQ models. In order to address this issue, a new expression for elements of the Jacobian matrix associated with PV buses has been proposed using the actual model of PV buses rather than using the model of PQ buses.

Let us assume that a single node k is connected to the slack bus. The current mismatch equations for this node in rectangular coordinates are given by,

$$\begin{bmatrix} \frac{V_{mk}}{V_k^2}\triangle P_k - \frac{V_{rk}}{V_k^2}\triangle Q_k \\ \frac{V_{rk}}{V_k^2}\triangle P_k + \frac{V_{mk}}{V_k^2}\triangle Q_k \end{bmatrix} = \begin{bmatrix} B{*}'_{kk} & G{*}'_{kk} \\ G{*}''_{kk} & B{*}''_{kk} \end{bmatrix} \begin{bmatrix} \triangle V_{rk} \\ \triangle V_{mk} \end{bmatrix}. \tag{2.19}$$

For PV bus k, Q_k is not known. Hence, $\triangle Q_k$ becomes dependent variable, then equation 2.19 becomes

$$\begin{bmatrix} \frac{V_{mk}}{V_k^2}\triangle P_k \\ \frac{V_{rk}}{V_k^2}\triangle P_k \end{bmatrix} = \begin{bmatrix} B{*}'_{kk} & G{*}'_{kk} & \frac{V_{rk}}{V_k^2} \\ G{*}''_{kk} & B{*}''_{kk} & -\frac{V_{mk}}{V_k^2} \end{bmatrix} \begin{bmatrix} \triangle V_{rk} \\ \triangle V_{mk} \\ \triangle Q_k \end{bmatrix}. \tag{2.20}$$

V_k is a known variable for PV bus k. An additional constraint, $\triangle V_k = 0$ is added to the equation 2.20 to eliminate the over determination. After adding this constraint the equation 2.20 reduced to

$$\begin{bmatrix} \frac{V_{rk}}{V_k^2}\triangle P_k \\ \frac{V_{mk}}{V_k^2}\triangle P_k \end{bmatrix} = \begin{bmatrix} B *''_{kk} - \frac{V_{mk}}{V_{rk}} G{*}''_{kk} & -\frac{V_{mk}}{V_k^2} \\ G *'_{kk} - \frac{V_{mk}}{V_{rk}} B{*}'_{kk} & \frac{V_{rk}}{V_k^2} \end{bmatrix} \begin{bmatrix} \triangle V_{mk} \\ \triangle Q_k \end{bmatrix}, \tag{2.21}$$

where,

$$G{*}'_{kk} = G_{kk} + \frac{real(E_i I_i)}{V_k^2}, \tag{2.22}$$

$$B{*}'_{kk} = -B_{kk} + \frac{imag(E_i I_i)}{V_k^2}, \tag{2.23}$$

$$B{*}''_{kk} = B_{kk} + \frac{imag(E_i I_i)}{V_k^2}, \text{ and} \tag{2.24}$$

$$G{*}''_{kk} = G_{kk} - \frac{real(E_i I_i)}{V_k^2}. \tag{2.25}$$

This reduction creates the power flow Jacobian matrix maintaining ($2n \times 2n$) matrix structure, with a new variable $\triangle Q_k$ replacing $\triangle V_{rk}$, for each PV bus.

2.2.2.1 Elements of Jacobian matrix after adding PV buses in power system

The Jacobian matrix of power network, having both, PQ and PV types of buses, has four types of (2×2) blocks, as described below.

i) Type 1 : The (2×2) diagonal block associated with PV bus k, is given by

$$Y_{kk}^* = \begin{bmatrix} B*''_{kk} - \frac{V_{mk}}{V_{rk}} G*''_{kk} & -\frac{V_{mk}}{V_k^2} \\ G*'_{kk} - \frac{V_{mk}}{V_{rk}} B*'_{kk} & \frac{V_{rk}}{V_k^2} \end{bmatrix}.$$

ii) Type 2 : The (2×2) diagonal block associated with PQ bus i, is given by

$$Y_{ii}^* = \begin{bmatrix} B'_{ii} & G'_{ii} \\ G''_{ii} & B''_{ii} \end{bmatrix}.$$

iii) Type 3 : The (2×2) diagonal block associated with a branch $l - k$, where k is a PV bus, is given by

$$Y_{lk}^* \begin{bmatrix} B_{lk} - \frac{V_{mk}}{V_{rk}} G_{kk} & 0 \\ G_{lk} - \frac{V_{mk}}{V_{rk}} B_{kk} & 0 \end{bmatrix}$$

iv) Type 4 : The (2×2) diagonal block associated with a branch $l - i$, where i is a PQ bus, is given by

$$Y_{li}^* = \begin{bmatrix} B_{li} & G_{li} \\ G_{li} & B_{li} \end{bmatrix}.$$

2.2.2.2 Calculation of Current mismatch

The current mismatch for PQ bus i is given by equations 2.8 and 2.9. For PV bus k, the current mismatch equation is given by

$$\triangle I_{rk}^* = \frac{V_{rk}}{V_k^2} \triangle P_k, \text{ and} \tag{2.26}$$

$$\triangle I_{mk}^* = \frac{V_{mk}}{V_k^2} \triangle P_k. \tag{2.27}$$

2.2.2.3 Bus voltage correction

Relation between voltage mismatch in polar coordinates and in rectangular coordinates are given by

$$\triangle V_k = \frac{V_{rk}}{V_k} \triangle V_{rk} + \frac{V_{mk}}{V_k} \triangle V_{mk}, \text{ and} \tag{2.28}$$

$$\triangle \theta_k = \frac{V_{rk}}{V_k^2} \triangle V_{mk} - \frac{V_{mk}}{V_k^2} \triangle V_{rk}. \tag{2.29}$$

After expressing the voltage mismatches in polar coordinates by equation 2.28 and 2.29, the updated voltage in polar coordinate at iteration $h+1$ is given by

$$V_k^{(h+1)} = V_k^{(h)} + \triangle V_k^{(h)}, \text{ and} \tag{2.30}$$

$$\theta_k^{(h+1)} = \theta_k^{(h)} + \triangle \theta_k^{(h)}. \tag{2.31}$$

2.3 Results and Discussion

The load-flow algorithms based on conventional Newton-Raphson (CNR) power flow, proposed modified current injection method (Mod-CINR), and conventional current injection (CINR) with different PV modelings have been implemented in MATLAB, and all algorithm were applied on two standard IEEE test systems, 30 and 50- bus test systems, and three practical unbalanced distribution test systems, case28, case55 and case82 (refer code in Annexure A, for data). It is to be noted that the standard IEEE distribution test systems with PV buses are not available in the literature, hence IEEE 30 and 57- bus test systems have been used for performing load flow assuming them as distribution systems where slack bus is assumed as root node and other generator buses are assumed as PV buses. In this study, all balanced test systems (i.e. IEEE 30 and 57-bus test system) have been modified to give unbalanced systems for studies in this section.

The test results on the performance of the above load-flow methods are presented in the following subsections. In this experiment, three representative CINR methods viz. CINR [28], Rev-CINR [30], and NR-CINR [37], discussed in section 2.1, suggesting different models PV buses have been chosen for comparison with Mod-CINR which implements the model of PV bus proposed in this thesis.

The comparison has been performed on following four characteristic performance parameters of any generic load flow algorithm: (i) size of Jacobian matrix (number of system variables), (ii) convergence property, (iii) ill-conditioned systems with different load condition, and (iv) ill-conditioned systems with large R/X ratio. Further, computation time of Mod-CINR has been compared with those of

CNR and FDBX to demonstrate its robustness and efficiency in terms of convergence and convergence speed respectively.

2.3.1 Size of Jacobian Matrix (Number of System Variable)

The sizes of Jacobian matrices of the above mentioned methods with CNR are compared, as shown in Table 2.1. It can be stated that the revised current injection based load flow method (Rev-CINR) needs more equations than other methods. On the other hand, the required equations are minimum in the NR and NR-CINR because both are using the same PV modeling where only one equation is required for PV bus. At the same time, CINR and Mod-CINR required the same number of equations of load flow, two for each bus.

Table 2.1: Size of Jacobian matrices of CNR, CINR, Rev-CINR, NR-CINR, and Mod-CINR (where n = Total number of buses, and p = number of PV buses in the system.)

Method	Order of Jacobian Matix	IEEE 30-bus ($p = 5$)	IEEE 57-bus ($p = 6$)
CNR	($2n$ - p - 2) x ($2n$ - p - 2)	53 x 53	106 x 106
CINR	($2n$ - 2) x ($2n$ - 2)	58 x 58	112 x 112
Rev-CINR	($2n$ + p - 2) x ($2n$ + p - 2)	63 x 63	118 x 118
NR-CINR	($2n$ - p - 2) x ($2n$ - p - 2)	53 x 53	106 x 106
Mod-CINR	($2n$ - 2) x ($2n$ - 2)	58 x 58	112 x 112

2.3.2 Convergence Property

The convergence property of these five algorithms is described by outlining the maximum active and reactive power mismatches alongside the number of iteration. Figures 2.1-2.5 demonstrate the convergence property of the six algorithms for the IEEE 30 bus test system. It can be seen from figures 2.1-2.5 that all the six

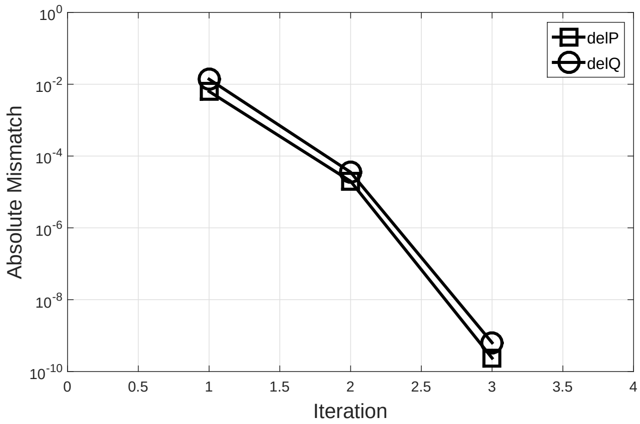

Figure 2.1: Convergence properties of CNR on IEEE 30 Bus system

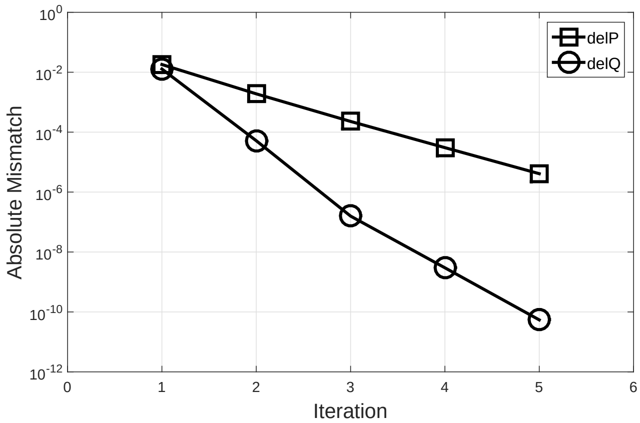

Figure 2.2: Convergence properties of CINR on IEEE 30 Bus system

algorithms show moderately fast convergence and the difference are only one or two iterations. Where the developed Mod-CINR has almost same convergence characteristics to conventional NR. At the same time, the number of iterations required by CINR and their other variants for solving power flow problem of IEEE 30 bus system is greater than the conventional CNR and Mod-CINR.

2.3.3 Ill-conditioned Systems with Different Load Condition

The sensitivity of enhanced representation for PV bus in CINR load flow (Mod-CINR) on different loading conditions is validated on the IEEE 30- bus system in comparison with conventional NR power flow and fast decoupled load flow (FDBX)

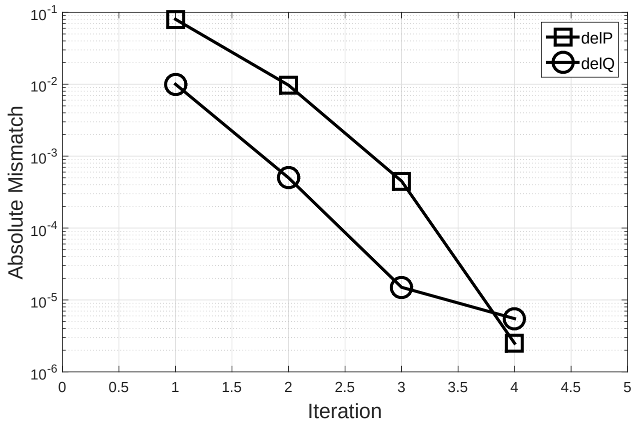

Figure 2.3: Convergence properties of Rev-CINR on IEEE 30 Bus system

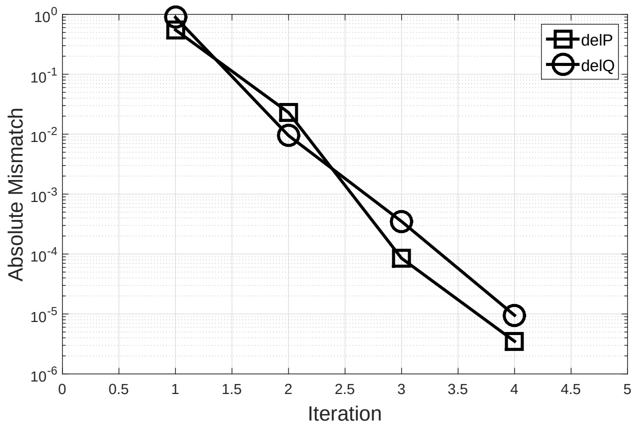

Figure 2.4: Convergence properties of NR-CINR on IEEE 30 Bus system

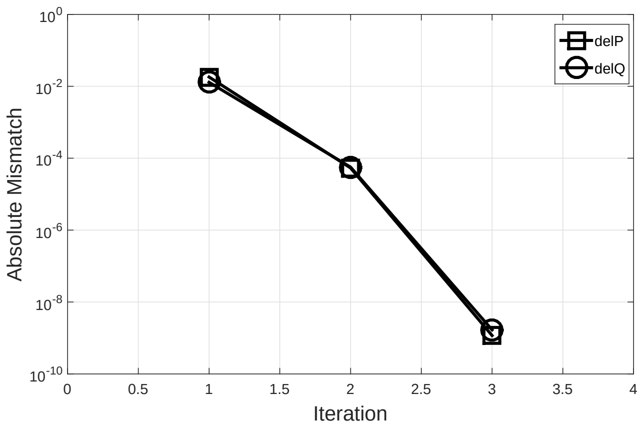

Figure 2.5: Convergence properties of Mod-CINR on IEEE 30 Bus system

techniques and different variants of CINR at the same tolerance equal to 1.E-5 p.u. The loading level is increased in the step of 40% and the results are reported in Table 2.2.

It can be detected that in all the six algorithms, as the loading level gradually increased close the maximum loading point, the required number of iterations grows respectively. However, it can be seen from table 2.2 that the developed Mod-CINR load flow algorithm has adjacent convergence characteristics to the conventional NR. At the same time, the other variants of CINR require more iterations to converge with respect to proposed Mod-CINR and also they fail to converge as loading level factor is increased from 280% in case of IEEE 30 bus system.

Table 2.2: Comparison of performance of all NR methods under different loading conditions.(NC = no convergence)

Level Factor (%)	CNR	CINR	Rev-CINR	NR-CINR	FDBX	Mod-CINR
40	3	4	3	3	6	3
80	3	4	4	3	7	3
120	3	6	4	4	8	3
160	3	8	4	4	9	3
200	3	10	5	4	11	4
240	4	12	6	4	13	4
280	5	NC	NC	5	17	5
320	5	NC	NC	NC	26	5
360	6	NC	NC	NC	NC	6
400	NC	NC	NC	NC	NC	NC

2.3.4 Ill-conditioned Systems with Large R/X Ratios Condition

The reliability of the proposed CINR, Mod-CINR on ill-conditioned systems with large R/X ratios is inspected by increasing the line resistances of the IEEE 30-bus system. In this test, three different levels of R/X ratio: 300%, 350% and 400% of the original R/X ratio at different tolerances are used. The table 2.3 demonstrates the convergence behavior of all the six algorithms (CNR, CINR, Rev-CINR, NR-CINR, Mod-CINR, and FDBX) for the given ill-conditioned systems.

It can be seen from the table 2.3 that the convergence rates of the developed Mod-CINR and CNR on the ill-conditioned system at different tolerance values are fairly similar. On the other variants of CINR, they need more iterations than the developed Mod-CINR to converge particularly at high R/X ratio and high tolerance.

Table 2.3: Comparison of performance of all NR methods under different R/X ratio condition.(NC = no convergence, T = Tolerance (pu))

T	R/X Ratio	CNR	CINR	Rev-CINR	NR-CINR	FDBX	Mod-CINR
1.00E-02	300	2	4	4	3	8	2
	350	3	5	7	3	16	3
	400	4	11	7	5	NC	4
1.00E-03	300	3	7	4	3	10	3
	350	3	10	8	4	18	3
	400	5	NC	8	6	NC	5
1.00E-04	300	3	10	5	4	12	3
	350	4	NC	8	4	21	4
	400	6	NC	10	7	NC	5
1.00E-05	300	4	14	5	4	13	3
	350	4	NC	8	4	22	4
	400	6	NC	10	7	NC	6

2.3.5 Comparison of Computation Time with CNR and FDBX

The efficiency of the developed Mod-CINR on the different test system is investigated in comparison with CNR and FDBX algorithms. In this test, five different IEEE test system: 9, 14, 30, 57, and 118 and three unbalanced practical distribution test systems: case28, case55, case82 are used. The computation time of all algorithms on the different test system is reported in the table 2.4.

It can be observed from the table 2.4 that the proposed Mod-CINR takes less time to converge in the case of 9, and 14 bus system than FDBX and CNR methods. The computation time of Mod-CINR is increasing with the increase of a number of PV buses in the test system and at the same time, the computation time of FDBX is almost constant for every system. With respect to the CNR method, Mod-CINR needs less computation time to converge for all the test systems. It is worthy to note that other CINRs cannot be converged on a single test system due to high number of PV buses. Hence, they are not considered in this analysis.

Table 2.4: Computational Time (s) for CNR, $FDBX$, and $Mod - CINR$ algorithms on different IEEE bus system (NC: Not Converged)

IEEE Bus	CNR (s)	FDBX (s)	Mod-CINR (s)
9	0.02311	0.01122	0.00374
14	0.03404	0.01057	0.00479
30	0.25039	0.01102	0.02073
57	0.66943	0.01144	0.05697
118	2.26578	0.01229	0.37299
case28	0.28021	NC	0.021032
case55	0.61635	NC	0.043274
case82	1.16452	NC	0.134279

2.4 Conclusion

In this chapter, an improved CINR, Mod-CINR, load flow method has been presented. The developed load flow method uses new equations to model PV bus in current injection power flow formulation, which are based on real and imaginary parts of simple multiplication of voltages and currents of PV buses. The Mod-CINR load flow technique decreases the required number of equations and also achieves the convergence property similar to conventional CNR method particularly in the case of PV nodes. At heavily loaded and large R/X ratio conditions the convergence characteristics also improve. The results also demonstrate that the computation time of Mod-CINR is less than the FDBX methods in the absence of PV buses in systems. The experiments suggest that the performance of the improved method in comparison to other techniques is better in terms of convergence, efficiency, sensitivity and reliability. From the outcomes of studies, it can be concluded that the proposed algorithm Mod-CINR has following advantages.

1. Mod-CINR is more robust than other CINR based algorithm because it can solve a wide variety of power flow problems including systems having a large number of PV buses.

2. Mod-CINR is more efficient than the other algorithms such as CNR, CINR, Rev-CINR, and NR-CINR except for FDBX which cannot be employed in distribution systems due to large R/X ratio, while Mod-CINR provides better convergence speed as compared to CNR.

3. In Mod-CINR, PV buses are handled effectively as compared to other representative algorithms. It is because of the use of proposed equations for elements of the Jacobian matrix associated with PV buses.