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Constant Matrix Based Power Flow For Distribution Networks

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Abstract— This paper presents the results of an extensive study of several transmission and distribution power systems to explore applicability of the Constant Complex Jacobian Power Flow Model [1]. This method exhibits stable convergence and the paper also demonstrates that this method stands as an alternative to the Fast Decoupled Power Flow (FDLF) model [2,3]. In Constant Complex Jacobian Power Flow the Jacobian evaluated from the real form of power equations P-Q is expressed in the complex variable form exploiting the structure of the Jacobian. This Jacobian is triangularized at the beginning of the power flow solution and it is kept constant throughout the power flow solution. In FDLF [2] many assumptions are considered and two matrices [B'] and [B"] have to be triangulated, but in constant complex Jacobian power flow method only single constant matrix is to be triangulated. The results demonstrate that the constant complex Jacobian power flow model possess more stable convergence for both well-behaved and ill-condition systems when compared to FDLF. The memory usage is slightly more compared to the Stott`s FDLF model and the time due to single matrix triangulation is on the similar magnitude as that of Stott`s model. From the results, this paper suggests that Constant Complex Jacobian Power Flow Model is an alternative to the FDLF [2]. However this model has strong convergence characteristics for distribution networks when compared to Stott`s model [2].

Index terms-Alternative to FDLF, Complex, Distribution networks, General Power Flow and ill condition networks.

1 INTRODUCTION:

Power flow calculations are performed in system planning, operation planning and control of power system. The choice of a solution method for practical application requires a careful analysis of the comparative merits and demerits of the many available methods [4] in such respects as storage, speed and convergence characteristics. Requirements of the specific application and computing facilities are also play the major role in the choice of the method. The difficulties arise from the fact that no one method possesses all the desirable features suitable for all cases of networks and situations.

In order to develop a simple and efficient power flow model, many decoupled polar versions of Newton Raphson method have been attempted for reducing memory requirement and computation time involved for power flow solution. Among several decoupled versions, the Fast Decoupled Load Flow model (FDLF) developed by Stott and Alsac [2] possibly is the most popular one frequently used. This method utilizes few justifiable assumption, apart from usual P-θ and Q-V decoupling, such as $\cos\theta \approx 1$, $G_{ij} \sin\theta \ll B_{ij}$ and $Q_i << B_{ii} V^2_i$ to obtain the Jacobian like matrices [B'] and [B"] and are held constant during the solution process.

Certain additional assumptions also have been employed to improve the convergence property of the FDLF model [2].

These assumptions are:

While forming [B'], parameters such as shunt reactances and off-nominal in-phase transformer taps are omitted.
Line series resistances are neglected while forming [B"].

The above additional assumptions have significant effect on the convergence property of the FDLF model [2]. But this method faces the problem for ill conditioned networks.

Later V.Bapi Raju et al [3] in which an efficient compensation technique (which is discussed later in this paper also) is used for Q-limit enforcement problem at PV buses so as to develop a General Purpose Fast Decoupled Power Flow Method (GFDPF)[3]. In GFDPF model, all the network shunts are considered as the impedance loads and are reflected in the bus power mismatch vector. A GFDPF model has the convergence property close to that of usual Stott's FDLF model for well-behaved systems but shows much better convergence property for ill-conditioned situations.

In GFDPF [3] and FDLF [2] models many assumptions are taken and two matrices i.e., [B'] and [B"] have to be triangulated. These assumptions have degrading effect on the convergence behavior.

An exploratory effort is made to develop an alternative power flow model, retaining the significant properties of the original Stott`s model from the memory requirement and triangulation time of the involved matrices with out resorting to (P-θ)-(Q-V) decoupling. The Jacobian in real form is formed with all the buses assumed to be PQ type. The resulting structure is exploited to represent it in the complex form paving the way for memory saving and less triangulation time. The details of formation of this model are presented in the next section. In Constant Complex Jacobian Power Flow Method the Jacobian is expressed in complex variable form and this Jacobian is triangulated once at the beginning and it is kept constant through out the power flow solution process. In constant complex Jacobian model only one or two assumptions are considered and only single matrix is to be triangulated. In Constant Complex Jacobian model also, in order to handle the Q-limit enforcement problem compensation technique (which is used in GFDPF model [3]) is used. Generally constant matrix methods exhibit reduced efficiency when dealing with Q-limit enforcements associated with the problems of bus type switching. M.Chan and Vladimir Brandwajn [5] have proposed the use of shunts at PV buses as long as reactive power limits are not violated. In the presence of violations, the matrix is refactorized using partial refactorization technique. Implementation of this technique requires higher programming skills without which the scheme might not achieved its full potential. The Constant Complex Jacobian model is a simple and an efficient technique which can handle the bus type switching due to Q-limit enforcement with out any implementation of partial refactorization techniques. In present paper Q-limit enforcement is not discussed deeply and it on further investigation. The Constant Complex Jacobian model exhibits best convergence for both well-behaved and ill-condition systems and this model also provides stable convergence and it exhibits fast convergence.

This paper presents the results of several transmission and distribution power systems for both well-behaved and ill condition by using FDLF and Constant Complex Jacobian model and compares these two methods. Investigations clearly reveal that Constant Complex Jacobian model stands as an alternative to the FDLF model.

Multiplying all the branch resistances or some branch resistances by a positive factor α simulates the ill condition, and varying the value of α varies the degree of ill condition. α=1.0 is corresponding to the base case values.

For the quick reference the Constant Complex Jacobian model is explained briefly in this paper.

2.PROBLEM FORMULATION

In the power system network, the net injected active and reactive powers at an i^{th} bus are given by

$$P_i = V_i \sum_{j=1}^{nb} V_j [G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}] \quad \text{----------(1)}$$

And

$$Q_i = V_i \sum_{j=1}^{nb} V_j [G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}] \quad \text{----------(2)}$$

Where V_i and V_j are the voltage magnitudes at i^{th} and j^{th} buses respectively.

$$\theta_{ij} = \theta_i - \theta_j$$

θ_i and θ_j are the bus angles of i^{th} and j^{th} buses respectively.

$G_{ij} + jB_{ij}$ represents the ij^{th} element of Y-bus.

NB is the total number of buses.

The linearized power flow equations of (1) and (2) are expressed in compact form as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J3 \\ J2 & J4 \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \quad \text{-----------(3)}$$

Where $\Delta P_i = P_{scheduled,i} - P_{calculated,i}$ ----------(4)

and $\Delta Q_i = Q_{scheduled,i} - Q_{calculated,i}$ ----------(5)

$[\Delta\theta]$ and $[\Delta V]$ are the corrections vectors for busbar angles and busbar voltages.

In equation (3) the sub-matrices J1 and J4 have dissimilar dimensions due to absence of Q-V equations of PV buses.

Fast-Decoupled Load Flow:

Stott shaped the equation (3) by utilizes some justifiable network assumptions as

$$\left[\frac{\Delta P}{V}\right] = \left[B' \right] [\Delta\theta] \quad \text{----------(6)}$$

And $$\left[\frac{\Delta Q}{V}\right] = \left[B'' \right] [\Delta V]. \quad \text{----------(7)}$$

General Purpose Power Flow Model:

In this method some additional assumption to Stott model are employed in order to reduce the parameters involved in the formation $[B']$, $[B'']$ and to handle the bus type switching.

The assumptions are

All network shunt reactances such as line charging reactances, external reactances located at buses and shunts formed due to π representation of off-nominal in-phase transformers are lumped at each bus are treated as constant impedance loads.

All the buses are assumed to be PQ type while forming the Jacobian like $[B']$ and $[B'']$ with a flat voltage start at 1.0 p.u. The treatment of PV buses will be considered later.

By incorporating the above assumptions the resulted FDLF equations are

$$\left[\frac{\Delta P'}{V}\right] = \left[B' \right] [\Delta\theta] \quad \text{-----------(8)}$$

and $$\left[\frac{\Delta Q'}{V}\right] = \left[B'' \right] [\Delta V] \quad \text{-----------(9)}$$

Where,

$$\Delta P_i' = P_{scheduled,i} - P_{calculated,i} - P_{shunts,i} \quad \text{------(10)}$$

$$\Delta Q_i' = Q_{scheduled,i} - Q_{calculated,i} - Q_{shunts,i} \quad \text{----(11)}$$

$P_{shunts,i}$ and $Q_{shunts,i}$ are the real and reactive powers due to lumped shunts at the i^{th} bus.

The dimension of the Jacobian $[B']$ is (NB-1) X (NB-1) and $[B'']$ is (NB-NPV-1) X (NB-NPV-1) in equations (6) and (7) (where NPV is the number of voltage controlled buses), but in equations (8) and

(9) the dimension of $[B']$ and $[B'']$ are same of (NB-1) X (NB-1).

A large value 'W'=(1.0/Xsh) (Xsh is chosen as 0.0001) is added to diagonals representing Q-V equations of PV buses in the $[B'']$ matrix of equation (9) in order to mask out the effect of the presence of Q-V equations of PV buses. This has the effect of maintaining the $\Delta V \cong 0$ for the incremental power flow model such that the specified bus voltage magnitudes are maintained constant at PV buses.

The $\left[\frac{\Delta Q'}{V}\right]$ terms related to voltage-controlled buses, which are in PV status, are always set zero.

Constant Complex Jacobian Power Flow Model:

The assumptions made in the Constant Complex Jacobian Power Flow Model are also same as in GFDPF.

The assumptions are

All network shunt reactances such as line charging reactances, external reactances located at buses and shunts formed due to π representation of off-nominal in-phase transformers are lumped at each bus are treated as constant impedance loads.

All bus voltages are assumed to be of $1.0\angle 0°$ at the beginning of the iterative process.

In the beginning all bus are assumed to be of PQ type. The treatment of PV buses will be considered later.

With these assumptions, equation (3) takes the form as

$$\begin{bmatrix}\Delta P' \\ -\Delta Q'\end{bmatrix} = \begin{bmatrix}-B & G \\ G & B\end{bmatrix}\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} \quad \text{----------(12)}$$

Where, $\Delta P`$ and $\Delta Q`$ are same as in equations (10) and (11).

The equation (12) can be written in complex form as

$$[\Delta P' - j\Delta Q'] = [J][\Delta V + j\Delta\theta]$$
$$where, [J] = [G + jB] \quad \text{----------(13)}$$

The Jacobian is Y-Bus devoid of shunts (excluding the slack bus row and column).

The order of the Jacobian is (NB-1) X (NB-1).

The ΔQ terms related to voltage-controlled buses, which are in PV status, are always set zero.

Incremental Secondary Injections (ISIs):

The ISIs are provided at these PV buses which are not in PV status to drive the voltage deviations to zero. In order to estimate the correct quantities of these injections, it is assumed that these PV buses are shorted to reference bus in the incremental power flow model as far as $\Delta Q - \Delta V$ equations are concerned. Proceeding on the lines similar to fault studies, the final voltage deviations $[\Delta V_{pv}^{f}]$ should be zero due to connection to the reference bus.

Using Thevenin`s equivalent circuit approach,

$$[\Delta V_{PV}^{f}] = [\Delta V°][X_{Th}][\Delta I] \quad \text{--------(14)}$$

Where,

$[\Delta V_{pv}^{f}] = [0]$ are the final voltage deviations,

$[X_{Th}]$ is Thevenin reactance matrix seen from PV buses, which are in PV status and reference bus, and the elements are picked up from $[J]^{-1}$.

$[\Delta I]$ is a vector of incremental secondary injections to be provided at these buses to drive the voltage deviations to zero at PV buses and $[\Delta V°]$ are the voltage deviations at these buses prior to connecting them to the reference bus.

$$\left[\Delta I\right] = -\left[X_{Th}\right]^{-1}\left[\Delta V^{\circ}{}_{PV}\right] \quad \text{---------(15)}$$

The changes in incremental voltages and angles due to these ISIs can be obtained from equation (13) after making the following changes as in equation (16).

$$\left[\Delta\Delta V + j\Delta\Delta\theta\right] = \left[J\right]^{-1}\begin{bmatrix}0.0 + j0.0\\ 0.0 - j\Delta I\end{bmatrix} \quad \text{---------(16)}$$

The changes in incremental voltages and angles due to these ISIs can be obtained using superposition principle as

$$\left[\Delta V^{F} + j\Delta\theta^{F}\right] = \left[\Delta V^{\circ} + j\Delta\theta^{\circ}\right] + \left[\Delta\Delta V + j\Delta\Delta\theta\right] \quad \text{----------(17)}$$

Where ΔV^{F}, $\Delta\theta^{F}$ are the final voltage and angle corrections.

ΔV°, $\Delta\theta^{\circ}$ are the initial estimates as obtained from equation (13) prior to ISIs.

The above procedure is adopted during every iteration and at the end of each iteration; the voltages and angle are updated as

$$\left[\Delta V + j\Delta\theta\right]^{t+1} = \left[\Delta V + j\Delta\theta\right]^{t} + \left[\Delta V^{F} + j\Delta\theta^{F}\right] \quad \text{-----------(18)}$$

t - is the iteration count.

The above procedure is repeated for every iteration in order to provide incremental secondary in injections at PV buses.

The problem of Q-limit enforcement is on further investigation.

3. SYSTEM STUDIES

Studies are performed on IEEE-14, 30 bus systems, Gungor-25 bus test system and also 33, 15 bus distribution systems. A tolerance of 0.01MW/MVA on a 100MVA base (0.0001p.u.) is chosen. Maximum numbers of iterations are fixed at 25.0. So, in the result tables, 26.0 indicate solution is slow convergence, and for divergence DIV is used. Several systems are studied for unadjusted case.

The results are presented in table-1 and table-3 obtained for Stott`s FDLF model and two another models for transmission systems and distribution systems respectively.

These models are coded as

(000)-(111), representing line series resistances, line shunts and external shunts are neglected in forming $\left[B'\right]$ coded as (000) and all are considered in forming $\left[B''\right]$ coded as (111).

(100)-(000), representing line series resistances is considered, line shunts and external shunts are neglected in forming $\left[B'\right]$ coded as (100) and all are neglected in forming $\left[B''\right]$ coded as (000).

(100)-(011), representing line series resistance is considered, line shunts and external shunts are neglected in forming $\left[B'\right]$ coded as (100) and the series resistance is neglected and all shunts are considered in forming $\left[B''\right]$ coded as (011).

d) (000)-(100), representing line series resistance, line shunts and external shunts are neglected in forming $\left[B'\right]$ coded as (000) and representing line series resistances is considered, line shunts and external shunts are neglected in forming $\left[B''\right]$ coded as (100).

The results represented in table2 and tanle4 are obtained for Constant Complex Jacobian Model for several transmission systems and distribution systems respectively.

4. NUMERICAL RESULTS AND DISCUSSIONS

Computer codes had been developed for both FDLF and Constant complex Jacobian Models by exploiting sparsity. It is interesting to note that in table 2, the iterations taken for the power flow solution to converge remain unaltered for both well-behaved and ill condition case up to some degree of ill condition. In referring to table 1 for case (100-011) exhibits more or less stable convergence. When results presented in table1 are compared with table2, the results in table2 shows better stable convergence.

From the results of distribution systems, the results in table 4 revels that constant complex Jacobian works well, takes less iterations to converge the power flow solution and also this method exhibits more or less stable convergence for both well behaved and ill conditioned distribution systems.

The results in table-2, 3 clearly demonstrate that the Constant complex jacobian exhibits stable convergence and it takes less iteration for distribution systems to converge.

TABLE-1: FDLF RESULTS FOR SEVERAL SETS OF $B' - B''$ FOR BOTH WELL-BEHAVED AND ILL CONDITIONED CASES

B'-B"	Degree of ill condition					
	1.0	1.5	2.0	2.5	3.0	3.5
(000)-(111)	4	5.5	8.5	11.5	16.5	23.5
(100)-(000)	4.5	5.5	5.5	6.5	6.5	6.5
(100)-(011)	4.5	5.5	5.5	5.5	6.5	6.5

TABLE 1.1 IEEE-14 BUS SYSTEM

B'-B"	Degree of ill condition					
	1.0	1.5	2.0	2.5	3.0	3.5
(000)-(111)	6.5	8.5	11.5	15.5	22.5	26
(100)-(000)	5.5	6	7.5	8.5	9.5	12.5
(100)-(011)	5.5	6	7.5	8.5	9	12.5

TABLE 1.2 GUNGOR 25 BUS SYSTEM

B'-B"	Degree of ill condition					
	1.0	1.5	2.0	2.5	3.0	3.5
(000)-(111)	3.5	6.5	8.5	12.5	18.5	26
(100)-(000)	4.5	5	5	6	7	8.5
(100)-(011)	4.5	5	5	6	7	8.5

TABLE 1.3 IEEE-30 BUS SYSTEM

TABLE2: CONSTANT COMPLEX RESULTS FOR BOTH WELL-BEHAVED AND ILL-CONDITIONED CASES (WITH OUT Q-LIMIT ENFORCEMENTS).

DIFFERENT SYSTEMS	Degree of ill-condition					
	1.0	1.5	2.0	2.5	3.0	3.5
IEEE 14 bus system	4	4	4	4	6	7
Gungor 25 bus system	6	6	6	7	10	14
IEEE 30 bus system	4	4	4	6	7	10

TABLE3: FDLF RESULTS FOR DISTRIBUTION SYSTEMS AND FOR BOTH WELL-BEHAVED AND ILL-CONDITIONED CASES

Distribution Systems	*B'-B"*	Degree of ill condition					
		1.0	1.5	2.0	2.5	3.0	3.5
15 bus system	(100)-(000)	5.5	6.5	7	9	10	12
	(000)-(100)	5	7	8.5	10	12.5	15.5
33 bus system	(100)-(000)	7.5	9	12	16	26	26
	(000)-(100)	8.5	12.5	17.5	25	26	26

TABLE4: CONSTANT COMPLEX JACOBIAN RESULTS FOR DISTRIBUTION SYSTEMS AND FOR BOTH WELL-BEHAVED AND ILL-CONDITIONED CASES

Distribution Systems	Degree of ill-condition					
	1.0	1.5	2.0	2.5	3.0	3.5
15 bus system	3	4	4	5	5	6
33 bus system	6	7	8	10	12	15

5.CONCLUSIONS

- FDLF Stott model [2] faces severe problem with ill-conditioned networks, this ill condition problem is overcome by the GFDPF [3]. But, FDLF and GFDPF so many network assumptions are considered.
- A simple and efficient model Constant Complex Jacobian model is developed without any assumptions.
- The Constant complex Jacobian model exhibits more stable convergence for both well-behaved and ill condition systems.
- The Constant complex Jacobian model works well for distribution systems and takes less iteration to converge and exhibits stable convergence for both well-behaved and ill condition.

The above reasons reveal that the Constant Complex Jacobian is a simple and efficient power flow model that can apply for both transmission and distribution systems and it is an alternative to the FDLF.

6.REFERENCES

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