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불량계통을 위한 변형 고속분할 조류계산법

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〈요 약〉

불량한 전력계통에서의 조류계산시 수렴성을 개선하기 위하여 변형된 고속분할법을 제안하였다. 이 산법은 매 반복 삼각화 직접법 단계에서 구해지는 해를 즉시 전압과 위상각 수정에 활용되도록 변형시킨 것이다. 제안한 변형산법을 IEEE 테스트 계통에 적용하여 기존의 산법과 비교하여 본 결과, 정상계통에서는 수렴성이 뒤지나 불량계통에서는 수렴성이 우수함을 알 수 있었다.

Modified Fast-decoupled Load Flow Algorithm for Ill-conditioned Systems

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〈Abstract〉

This paper presents a modified algorithm to improve the convergency of fast-decooupled load flow (FDLF) method. The specific feature of proposed method is using of the most recent values of solution vector when solving the iterative recursive equations. This simple modification to standard FDLF method yields a more reliable convergence characteristics for ill-conditioned systems. A comparison of proposed method with the standard FDLF method is also presented for IEEE test systems.

Ⅰ. Introduction

The load Flow problem is concerned with the solution for the steady operating conditions of an electric power transmission system, and is performed at the stage of power system planning, operational planning, and operation/control. Load flows are increasingly being use in on-line environment, such as optimal load flow study and contingency analysis in energy control center.

Since 1956 when the first practical digital computer oriented method was proposed[1], a large number of solution algorithms have been proposed in the literature[2] which are attractive from the point of view of solution speed, accuracy, required stroage and easy programming, etc. Conventional Y-matrix iterative methods require minimal computer storage but converge slowly, and too often not at all. The incentive to overcome this deficiency led to the development of Z-matrix methods, which converge more reliably but require notable storage and speed when applied to large systems. Tinney and others proposed an efficient Newton-Raphson method with sparsity programmed ordered elimination technique.[3] Stott and Alsac developed fast-decoupled method which is reliable and extremely fast for load flow solution and contingency analysis.[4]

Fast-decoupled load flow(FDLF) method has been proven to be very fast and easily adapted to practical on-line control applications. However, poor convergency of FDLF algorithm occurs when the decoupling assumption is false. Recent papers[5-6] have presented an alternative algorithm which is claimed suitable for ill-conditioned systems, where FDLF failed to converge to solutions.

In this paper, a modified FDLF algorithm is proposed which is hybrid version of standard FDLF method and Gauss-Seidel process model. The Proposed algorithm is particularly effective for solving of ill-conditioned systems. It is varition of fast-decoupled method incorporating Gaussian elimination in such a way that the most recent information is always used at each step of algorithm ; similar to what is done in the Gauss-Seidel process. A comparsion of proposed method with the standard FDLF method is presented for IEEE 14,30 and 57 bus ill-conditioned test systems. The ill-conditioned system is made by trying to violate decoupling assumption by changing some line parameters.

II. Fast-decoupled Load Flow

The equations of load flow are written as a single set $\mathbf{F(X)}=0$ and solved by the formal application of generalized Newton(−Raphson) algorithm ;

$$X^{\nu+1}=X^{\nu}-[F'(X^{\nu})]^{-1}F(X^{\nu}) \qquad (1)$$

where $\mathbf{F'(X)}$ is the Jacobian of $\mathbf{F(X)}$. Eq. (1) can be split into two portions, namely, a correction part and part consisting of a set of linear equations, so that Eq. (1) is equivalent to the following equations ;

$$F(X^{\nu})=-F'(X^{\nu})\Delta X^{\nu} \qquad (2)$$

$$X^{\nu+1}=X^{\nu}+\Delta X^{\nu} \qquad (3)$$

The most popular and successful formulation is that in which $\mathbf{F}$ is the set of busbar active and reactive power mismatches and solution variables are the unknown busbar voltage angles and magnitudes. These equations can be written in a different notation as

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix}=0 \qquad (4)$$

and can be expressed in terms of polar components as

$$\Delta P_i=P_i^{sp}-V_i\sum_{j\in i}(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij})V_j \qquad (5)$$

$$\Delta Q_i=Q_i^{sp}-V_i\sum_{j\in i}(G_{ij}\sin\theta_{ij}-B_{ij}\cos\theta_{ij})V_j \qquad (6)$$

where

n=number of busses
P_i, Q_i=loads or injected power at i-th bus
V_i=voltages at i-th bus
$\theta_{ij}=\theta_i-\theta_j$
θ_i=angle of voltage at i-th bus
$G_{ij}+jB_{ij}$=admittance between nodes i and j
$j\in i$ implies "j takes the value of bus numbers connected to i-th bus"

The linear equation (2) appearing in Newton's formulation is given by

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix}^{\nu}=\begin{pmatrix} H & N \\ M & L \end{pmatrix}^{\nu}\begin{pmatrix} \Delta\theta \\ \Delta V/V \end{pmatrix}^{\nu} \qquad (7)$$

The details of this method are well documented in the literature.[9] The correction term $\Delta \mathbf{V}^{v}$ is usually divided by $\mathbf{V}^{v}$ to simplify the calculation of some of Jacobian matrix. The square Jacobian matrix in Eq.

(7) is highly sparse, and Eq. (2) is solved at each iteration by sparse programmed ordered elimination.[7]

Solution of Eq. (7) for each iteration involves calculation of Jacobian matrix elements. As this involves large calculation, decoupling procedure were developed.[4] By ignoring submatrices **N** and **M** in Eq. (7), the resulting linear equation becomes

$$[\Delta P]=[H][\Delta\theta] \tag{8}$$
$$[\Delta Q]=[L][\Delta V/V] \tag{9}$$

This decoupled method converges as reliably as the Newton's method. Its principal advantage lies in the saving on the storage for the Jacobian matrix of neglecting the coupling matrices **M** and **N**.

The decoupled method can be further simplified by making further physically justifiable simplication into Eq. (8) and (9). With this modification, the final fast-decoupled load flow equation becomes

$$[\Delta P/V]=[B'][\Delta\theta] \tag{10}$$
$$[\Delta Q/V]=[B''][\Delta V/V] \tag{11}$$

where

$$B'_{ij}=-1/X_{ij}$$
$$B'_{ij}=\sum_{j\in i}(1/X_{ij}),\quad B''_{ij}=-B_{ij}$$

Both [B′] and [B″] are real and sparse and have structures of [H] and [L] respectively. Since they contains only network admittances, they are constant and need be evaluated once only at the begining of the study. If phase shifter are not present both [B′] and [B″] are symmetrical.

As in the standard fast-decoupled load flow, solution procedure involves decomposition of [B′] and [B″] into triangular matrices initially and solution of Eq. (10) and (11) repeatedly calculating the left side with new value of unknowns.

III. Modified Algorithm

A set of n linear equations (10) and (11) can be expressed

$$[A][X]=[b] \tag{12}$$

where [**A**] is a nonsingular matrix, [**b**] is a given independent vector, and [**x**] is an unknown solution vector. If [**A**] is large and sparse, it is adventageous to exploit the sparsity by performing the factorization and solutions by sparse matrix methods.[3],[7]

The modified algorithm is equivalent to solving the expanded equations:

$$\begin{pmatrix} a^1_{11} & a^1_{12} & \cdots & a^1_{1n} \\ & a^2_{22} & \cdots & a^2_{2n} \\ & \vdots & & \\ & & \vdots & \\ & & & \vdots \\ & & & a^n_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} b_1^0 \\ b_2^0 \\ \vdots \\ \vdots \\ \vdots \\ b_2^0 \end{pmatrix} \tag{13}$$

The m-th equation is solved for **x**

$$x_m{}^v=x_m{}^0+a^m{}_{mm}\,[b_m{}^0-\sum_{k=m+1}^{i=m+v}a^m{}_{mk}(X_k{}^{i-k}-x)] \tag{14}$$

The procedure is to assume a set of starting values for **x** and then calculate new values by substitution into Eq. (14) These values are used as new estimates and iterations are continued until some criterion is met. Incorproated into the solution of fast-decoupled load flow, modified algorithm is used for solving the power mismatch Jacobian matrix equations.

For a set of Eq. (10) start the procedure with a set of starting values;

$$\Delta\theta_k=\theta_k{}^{v-k}-\theta_k{}^0 \tag{15}$$

for i>0 and 1<k<n, then the sequence of operation becomes

$$\Delta\theta_m{}^v=\frac{1}{B^m{}_{mm}}\,[\frac{\Delta P^0{}_m}{V_m{}^0}-\sum_{k=m+1}^{i=m+v}B^m{}_{mk}\Delta\theta_k] \tag{16}$$

and is need as the initial vector for the next iteration.

The computational steps for modified FDLF algorithm are given as follows:

$$\theta_m^v = \theta_m^v + \Delta\theta_m \quad (17)$$

$$\Delta P_m^0 = P_m^{sp} - P_m(\theta_k^{i-k}) \quad (18)$$

Ⅳ. Test Results

Numerical tests were carried out on the three IEEE test systems, i.e., 14, 30, and 57 bus systems using the proposed and standard FDLF algorithm.

Fig. 1-4 gives comparison of convergence characteristics of various systems. Numerical values obtained from the figures are summerized in Table 1. For all studies the initial voltages assumed are 1+j0 for all the P-Q bussed. The convergence criterion is taken to be 1.0×10^{-4}[MW/Mvar] mismatch.

It is necessary to construct the ill-conditioned case from well-conditioned test system for comparative study. This is done by adding a amount of resistive value of lines in each system, thus the decoupling assumption (X/R is greater than unity) are violated. For 14 bus case, line parameters which includ transformer are added from base case to 0.2+j0. For 30 bus and 57 bus cases, same ones are added to 0.3+j0.

According to the case studies, it can be observed that proposed algorithm has more reliable convergency than standard method for ill-conditioned system. On the other hand, for well conditioned case, standard method requires less iterations to obtain the final solution.

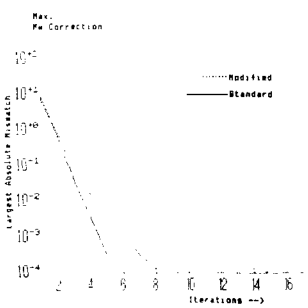

Fig. 1 Convergence characteristics of 14 bus well-conditioned case

The proposed method takes slightly more computing time per iteration than that of standard method. This is mainly because of updating the residual vector when solving the Gaussian elimination. However, this disadventage is offset by the superiority of proposed method for ill-conditioned systems.

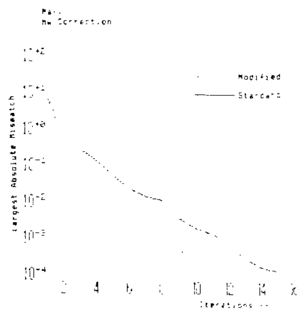

Fig. 2 Convergence characteristics of 14 bus ill-conditioned case

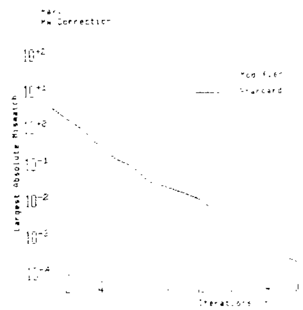

Fig. 3 Convergence characteristics of 30 bus ill conditioned case

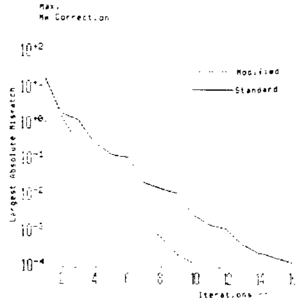

Fig. 4 Convergence characteristics of 57 bus ill conditioned case

Table 1. Comparison of iterations between proposed and standard method

System type	Well-conditioned		Ill-conditioned	
	Proposed	Standard	Proposed	Standard
14 bus	7	5	11	15
30 bus	7	5	11	17
57 bus	8	5	10	16

V. Conclusion

This paper presents a modified algorithm to improve the convergency of fast-decoupled load flow. Presented algorithm is a variation of conventional method incorporated with Gaussian elimination what is done in the Gauss-Seidel process. The procedure adopted in this algorithm is relatively simple and can be easily incoporated in the existing fast-decoupled methods. Compared to standard method for IEEE test systems, the proposed methods is particularly effective for solving ill-conditioned systems. It is visualized that proposed method should appeal to practising engineers for obtaining guaranteed load flow solutions.

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