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A parallel distributed computing framework for Newton–Raphson load flow analysis of large interconnected power systems

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ABSTRACT

This paper proposes a simple parallel and distributed computing framework for the conventional Newton–Raphson load flow (NRLF) solution of large interconnected power systems. The proposed approach is based on message-passing distributed-memory architecture with separate workstations, and involves the piecewise analysis of power systems utilizing the network tearing procedure. The NRLF solution method, applied to each torn system at the selected buses, employs the matrix inversion lemma consisting of the factorization, forward elimination and back substitution procedures. The computational requirements of the state-of-the art parallel algorithm to obtain the correction vector involved in the back substitution procedure is reduced with the proposed approach in which the back substitution is carried out in parallel taking into account the split buses, rather than the order in which the forward elimination is performed. The investigations are carried out on the IEEE 118 bus standard test system in a Redhat Linux based 100 Mbps Ethernet LAN environment. The investigations reveal that the proposed method is significantly faster than the conventional NRLF and also the NRLF based on the state-of-the-art parallel algorithm, and thus finds potential applications for the real-time load flow solution of both regulated and deregulated power systems distributed over large geographical areas.

Introduction

Load flow analysis is one of the most frequently performed studies in power systems for the determination of its steady operating state for a given load demand, the results of which is required for system planning, operation and control. Load flow solution provides the bus voltage magnitudes and angles and hence the power injections at all the buses and power flows though the transmission lines, cables and transformers. As the load flow problem involves the simultaneous solution of non-linear algebraic equations, the solution technique is iterative in nature. Over the years enormous amount of research and development efforts have been applied and consequently various methods have been evolved for the solution of the load flow problem. Of all these methods, Newton–Raphson approach or its derivatives have emerged as the most popular ones due to their quadratic convergence properties and the ability to handle ill-conditioned systems. Further, the number of iterations required for a specified accuracy is significantly less than the other techniques and are practically independent of the system size. The conventional NRLF problem formulation is given by [1]

$$\begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{1}$$

The H, N, J and L are the sub-matrices of the Jacobian matrix. Power flow solutions are usually started with a flat voltage start assumption of 1 p.u. for the bus voltage magnitudes and zero degrees for bus voltage angles. With these values, the real and reactive powers at Bus K are calculated for all buses as

$$P_{K\ calculated} = \sum_{M=1}^{n} V_k V_m (G_{KM}\ Cos\ \delta_{KM} + B_{KM}\ Sin\ \delta_{KM}) \quad \text{for } K = 1, 2, \ldots, n \tag{2}$$

$$Q_{K\ calculated} = \sum_{M=1}^{n} V_k V_m (G_{KM}\ Cos\ \delta_{KM} + B_{KM}\ Sin\ \delta_{KM}) \quad \text{for } K = 1, 2, \ldots, n \tag{3}$$

Then the bus power mismatches are

$$\Delta P_K = P_{K(specified)} - P_{K(calculated)} \tag{4}$$

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Nomenclature

P_i, Q_i	real power and reactive power at bus i	P_G, Q_G	real and reactive power generation
R, X	transmission line resistance and reactance	P_D, Q_D	real and reactive power demand
Y_{ik}	admittance of line connecting buses i and k	ΔP, ΔQ	real and reactive power mismatches
G_{ik}, B_{ik}	conductance and susceptance of lines connecting buses i and k	n	number of buses
		δ	bus voltage angle
V_i	complex bus voltage of bus i	θ	admittance angle

$$\Delta Q_K = Q_{K(specified)} - Q_{K(calculated)} \tag{5}$$

All the elements of the Jacobian matrix are computed by partial differentiation of Eqs. (2) and (3) and the NRLF equations are solved for the corrections in bus voltage magnitudes ($\Delta V/V$) and bus voltage angles ($\Delta\delta$). Modified values for bus voltage magnitudes and voltage angles are obtained by adding the corrections to the respective assumed values. The iterations are repeated until $|\Delta P_K| \leqslant \varepsilon$ and $|\Delta Q_K| \leqslant \varepsilon$ for all i where ε is the desired tolerance.

The major concerns of the application of the conventional NRLF analysis to practical large power systems are the need for high memory and computational requirements. With the development of semiconductor memories and powerful processors, it is not difficult to solve systems of a particular geographical area using NRLF or its derivatives such as Fast Decoupled Load Flow (FDLF) methods. However, present day power systems are largely interconnected, and can be considered as an integration of several subsystems distributed over widely separated geographical areas, particularly in the case of a national power grid. Monitoring and control of a national grid, comprising of several regional grids which themselves gets divided into smaller state grids, as a single entity has become more complex as the system data related to each state or regional grid are available only in the control centers of the respective grids and hence the load flow computations at a central location has become more difficult.

In addition, many of the present day power systems worldwide are operating in a deregulated market environment so as to encourage privatization in the electricity sector. This set up is intended to remove the monopoly of the conventional power system structure and at the same time to increase competition among the various associated supply providers which may lead to quality power supply at reduced tariff along with value added services. The load flow computations in a deregulated power system with independent supply providers may link several geographically separated utilities, and thus necessitates the distribution of the total computations corresponding to these utilities or areas among the computers of the respective regions rather than a completely centralized load flow implementation.

Emergence of parallel and distributed computing systems has attracted the attention of researchers to apply these techniques for power flow solutions of such power systems. While the conventional NRLF involves the repeated solution of a set of simultaneous equations with highly sparse coefficient matrix [1], parallel solution of large systems involves tearing the system into subsystems and solving the subsystems in parallel [2]. The solutions of individual subsystems are to be corrected so that it is the same as the one piece solution. Kasthuri and Potti [3] has proposed an exact piecewise Newton–Raphson algorithm in which a large power system is torn into subsystems by cutting and removing interconnecting lines. A more efficient algorithm for tearing the power system by splitting suitable nodes of interconnection has been proposed by Potti [4]. The advantage of this method is that it reduces the number of additional right hand side vectors and the size of the inter-subdivision matrix. Both algorithms block-diagonalizes the system matrix and make use of the Matrix Inversion Lemma. H.Sasaki, K.Aoki and R.Yokoyoma [5] has proposed an effective parallel computation algorithm based on the matrix inversion lemma. This algorithm, referred to in this paper, as SAY PD algorithm, involves the following major steps:

i. Solve the subsystems in parallel.
ii. Form the inter-subdivision matrix, its right hand side vector and then solve the inter-subdivision equation.
iii. Apply correction to the subsystem solution in parallel.

This algorithm involves a serial step. This is because the rows of the solution vectors for the subsystem corresponding to the 'tearing axis' are required for computing the inter-subdivision equations. Hence the second step can be carried out only after the completion of the first step. In the algorithm proposed in this paper, as this serial step is avoided, it is significantly faster than the SAY PD algorithm.

Significant research has been done for distributed power flow solutions [6,7]. Message-passing techniques have been applied to synchronize the actions of work stations in a distributed environment [7]. Parallel solution of large systems thus involves tearing the system into subsystems and solving the subsystems in parallel. Piecewise methods developed for reducing memory requirements are suitably modified for parallel execution. This paper involves the reformulation of the conventional NRLF algorithm in a parallel and distributed computing framework for fast and accurate load flow analysis of large interconnected power systems.

The rest of the paper is organized as follows: After giving the details of the proposed parallel and distributed processing approach in section 'Proposed parallel and distributed processing algorithm', its application to NRLF is discussed in section 'Application of the parallel and distributed algorithm for NRLF analysis'. This is followed by the test system details and simulation results in section 'Test system and simulation results' and the conclusion in section 'Conclusion'.

Proposed parallel and distributed processing algorithm

The set of simultaneous equations given by Eq. (1) representing a power system with n nodes is written for simplicity as

$$Ax = b \tag{6}$$

where A is an $[n \times n]$ matrix. As shown in Appendix A, the matrix A can be block-diagonalized by splitting suitable nodes of interconnection in the network and thus the equation becomes

$$Bx' = b' + Ky \tag{7}$$

where
B: $[(m+n) \times (m+n)]$ block diagonal matrix, with s blocks,
K: $[(m+n) \times m]$ matrix, y: $(m \times 1)$ vector,
x': $[(n+m) \times 1]$ vector, b': $[(n+m) \times 1]$ vector.

m is equal to the number of nodes those are split to block-diagonalize the system matrix. The number of blocks is equal to the number of subsystems. K is simple in structure, each column