

Iterative method for detecting and localizing islands within sparse matrixes using DSSim-RT

D. Montenegro

Department of Electronic Engineering
Universidad Santo Tomás
Bogotá, Colombia

Department of Electrical and Electronic Engineering
Universidad de los Andes
davismontenegro@usantotomas.edu.co

Abstract— Nowadays, simulation for power flow analysis of distribution systems must consider their separation in several islands. This separation is the result of management activities such as reconfiguration, fault detection and isolation, among others. For power flow analysis the distribution system is represented as sparse matrix; however, if these islands are not considered the results can be inaccurate and inconsistent. There are several methods for detecting islands reported in literature, but these methods normally require that the Y matrix is organized in special form. This situation is not always possible because is the user who defines the order of the matrix when using simulation software. This paper presents an algorithm for detecting and localizing islands within sparse matrixes no matter the order of the elements of the matrix. By using graph theory, the incidence matrix of the power system can be transformed into its adjacent representation. With this matrix the interconnected elements are detected and classified. Then, with this new reference matrix the algorithm delivers number of islands, the suggested order for the columns of the Y matrix and more information. The aim is to simplify the localization of islands with a simple algorithm, which can be implemented using any programming language. This method is used in DSSim-RT, which is a simulator based in OpenDSS, for detecting islands and performing the multithread power flow analysis of distribution systems in Real-Time.

Keywords—*graph theory; power system simulation; power system analysis; real time systems.*

I. INTRODUCTION

Smart Grid technologies combine several challenges to address when analyzing power systems. Particularly, in the case of Distribution Systems (DS) the integration of Distributed Energy Resources (DER) is a major topic [1]. These change the power flow direction within the grid, which makes difficult the coordination of management activities by the Energy Management System (EMS) [2, 3].

These new technologies are integrated to the DS through Advanced Distribution Automation (ADA) [4, 5], which is a set of management activities for ensuring the Security, Quality, Reliability and Availability (SQRA) of the power system [6]. These management activities includes feeder reconfiguration [7, 8], Volt/VAr control [9, 10], fault location and isolation [11], among others; changing the DS topology when they are

performed by the EMS. As result, the DS can be separated in several islands, which can make difficult the load flow analysis of the DS [12]. This analysis requires a Y matrix built in a diagonal form for reducing the computational burden, but this form can be lost when operations such as the mentioned above occur.

The literature registers several methods for detecting islands within sparse matrixes. Methods such as Approximate minimum degree (AMD) and its different versions such as COLAMD [13, 14], have been used for addressing this problem. However, these applications do not fit for all situations and normally require a special form for detecting all the islands.

The methods mentioned above have been used for reordering a symmetric sparse matrix before their factorization, which is the method used for solving DS power flows using direct methods [15, 16]. Furthermore, partitioning methods such as Diakoptics [17, 18] require the identification and location of islands as part of their tearing process.

This paper presents an algorithm for detecting and locating islands within sparse matrixes no matter the order of the elements of the matrix. By using graph theory, the incidence matrix of the DS can be transformed into its adjacent representation. With this matrix the interconnected elements are detected and classified. Then, with this reference matrix the algorithm provides the number of islands, the suggested permutation for the columns of the Y matrix, and more information related with the location and size of each one.

The aim with this algorithm is to simplify the localization of islands, and make of it suitable for being implemented using any programming language. This method is used in DSSim-RT [19, 20], which is a simulator based in OpenDSS [21], for detecting islands and performing the multicore power flow analysis of the distribution systems in Real-Time.

This paper is divided in four sections:

- A brief review about the methods used for detecting elements strongly connected within sparse matrixes.
- The description of the algorithm and its features.

- The results when applying the proposed algorithm over a DS.
- Conclusions.

II. ELEMENTS STRONGLY CONNECTED WITHIN SPARSE MATRIXES

The detection of islands within sparse matrixes has been a topic of interest for several years. Due the correct location of these, to propose a convenient order of the matrix elements is possible. This order is highly important for solving linear equation sets by using direct methods [22].

These methods are based in graph theory for detecting strongly connected elements within the matrix, which are reordered for producing less fill-in and computational work for solving the system [23]. The problem to solve is as follows:

$$Ax = b \quad (1)$$

The aim is to make A suitable for finding b using factorization methods such as Cholesky, LU, among others [24]; avoiding matrix inversion for computing direct solutions of large sparse systems. These techniques have been extended for covering unsymmetrical systems, which results in a problem NP-Complete [25]; demanding the use of heuristics for finding the adequate permutation.

For finding the reordering required the methods mentioned above only the structure of the matrix is used; this way, the computational burden is reduced using simpler representations such as matrixes branch to node.

The first version of these algorithms is registered in literature in the 60's. This algorithm is a symmetric equivalent of the Markowitz method [26], and is called *optimal ordered triangular factorization* [27]. Then, this method was improved by adding graph theoretical models [28] and are called the *minimum degree algorithms*. Since then, there are several works around this topic looking for improving the computational burden and memory use; but keeping the original idea of selecting a group of nodes of minimum degree.

However, this work deals with the problem of island location when the DS topology changes [29]. This is a different focus to the ones presented by the algorithms mentioned above, which are focused into searching the block triangular form (BTF) for solving the sparse linear system.

By considering the graph theory and several characteristics of the mentioned above, this work propose a simple algorithm for addressing the proposed problem.

III. LOCATION OF ISLANDS WITHIN SPARSE MATRIXES ACCORDING TO THE GRID TOPOLOGY

For topological analysis, power systems can be represented with a directed graph [30, 31]. These graphs describe a set of nodes connected by edges, which have associated a direction. These graphs are represented as incidence matrix. The cells of this matrix are occupied by 0 or 1 depending on if a branch is connected to a node; the sign of the digit defines its direction as shown in Fig. 1.

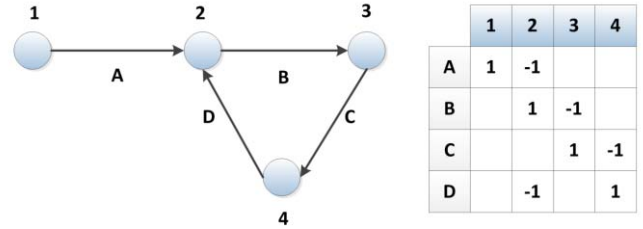


Fig. 1. Directed graph and its incidence matrix. The empty cells correspond to 0 values.

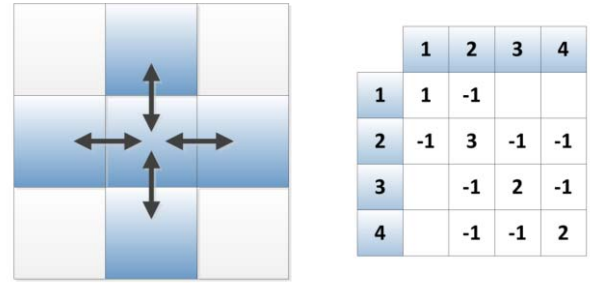


Fig. 2. Adjacent matrix and strongly connected elements.

However, due the radial nature of DS the incidence matrix is non symmetrical. This representation can be translated into another called the adjacent matrix using the following expression:

$$Ad = I^T I \quad (2)$$

In equation (2) Ad is the adjacent matrix and I is the incidence matrix. The adjacent matrix is symmetrical and describes how the nodes are interconnected. The diagonal of this matrix corresponds to the number of nodes linked to the diagonal node. The other cells will have a value equal to -1 if they are connected to the node corresponding to the row/column.

The adjacent relationship between nodes defines if they are strongly connected. If any cell of a certain row/column of the adjacent matrix is different from 0 means that the nodes are interconnected. This concept is illustrated on Fig. 2.

So, by inspecting each column it is possible to determine if a certain set of nodes are connected to a reference. This procedure is iterative and can be performed using columns or rows due the matrix symmetry.

The proposed strategy consists into sweep each column searching for interconnected cells. Simultaneously, an index value is assigned for representing each cell interconnected in a matrix full with the same size of the adjacent matrix.

The index value will increment in 1 when the search for interconnected elements is finished for the selected column. As result, a matrix filled of indexes describing the islands will be obtained. This matrix is called the islands matrix.

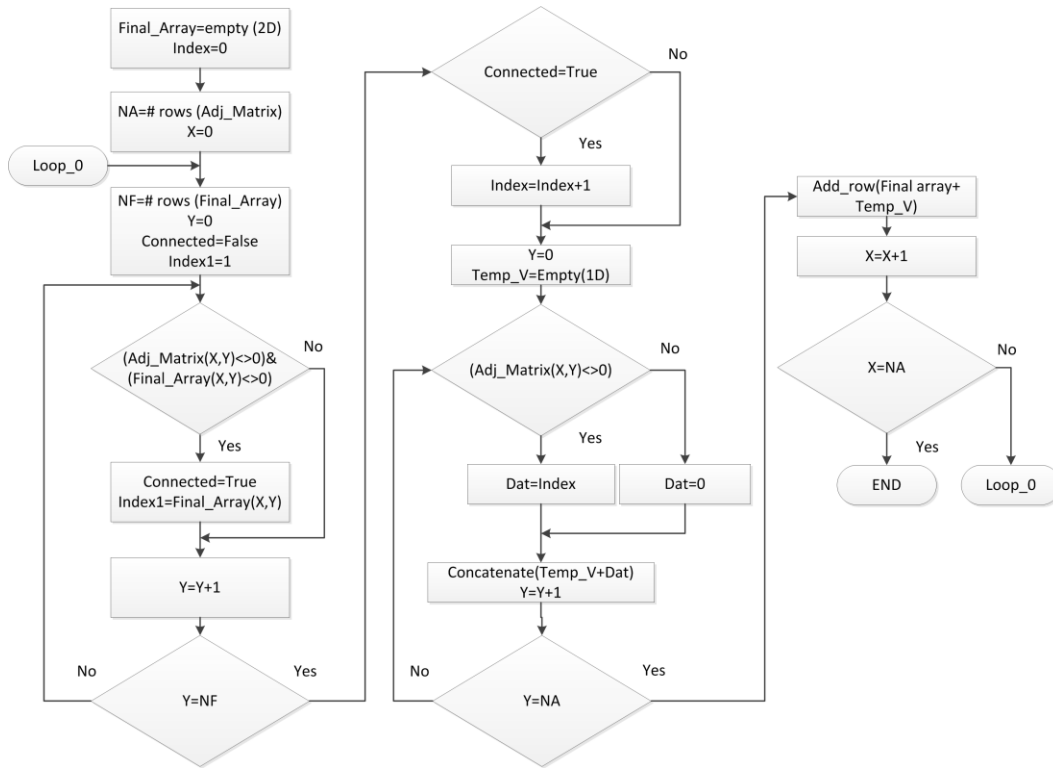


Fig. 3. Proposed algorithm for locating islands.

The proposed algorithm for finding islands is shown in Fig. 3. In this algorithm variables X , Y and $Index$ will deliver important information. Variables X and Y contain the coordinates of the cell evaluated. Once the algorithm finishes the variable $Index$ will contain the number of Islands found.

Moreover, the diagonal of the islands matrix (IM) describes the location of the island's components. By extracting this vector a permutation can be proposed for grouping each island cells. Then, this permutation can be applied to the Y matrix of the DS for identify clearly each island.

The permuted diagonal of the IM can be used for locate ach island; this way, they can be extracted for independent analysis or for being used in multithread algorithms.

IV. RESULTS

Consider the radial system shown in Fig. 4. This system includes a distributed generator, three residential loads and two industrial loads. Because there are two reclosers installed on the DS, there are four possible configurations for the system. These configurations are going to be explored for evaluating the performance of the algorithm.

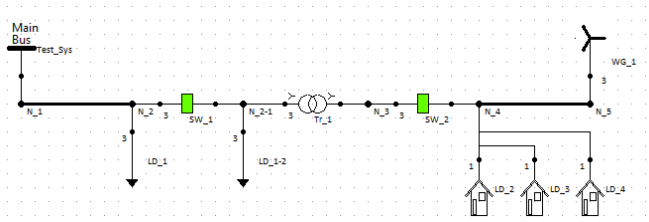


Fig. 4. Interconnected radial system.

This system is implemented using DSSim-RT, which provides the incidence matrix of the proposed DS. The basic version of OpenDSS do not provides this data; but using DSSim-RT/PC, the user can access this data by using the command 0x1D through the TCP server included [32].

The first configuration corresponds to the interconnected network, which means that both reclosers are closed. The IM obtained for this network after applying the algorithm is shown on Fig. 5. As can be seen in Fig. 5 the order of the nodes does not correspond to the order in Fig. 4. However, because the system is interconnected the permutation suggested is equal to the current distribution.

As consequence, the Y matrix remains the same as seen in Fig. 6. In this figure, the colored cells correspond to the non-zero values and the rest are zero.

	n1	n2	n4	n3	n5	n2-1
n1	1	1	0	0	0	0
n2	1	1	0	0	0	1
n4	0	0	1	1	0	1
n3	0	0	1	1	1	0
n5	0	0	0	1	1	0
n2-1	0	1	1	0	0	1

Fig. 5. IM obtained for the study case 1.

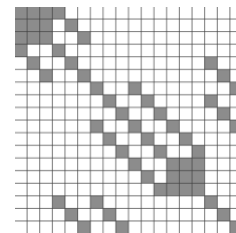


Fig. 6. Reordered Y matrix for the study case 1 (remains like the original).

	n1	n2	n4	n3	n5	n2-1
n1	1	1	0	0	0	0
n2	1	1	0	0	0	0
n4	0	0	2	2	0	2
n3	0	0	2	2	2	0
n5	0	0	0	2	2	0
n2-1	0	0	2	0	0	2

Fig. 7. IM obtained for the study case 2.

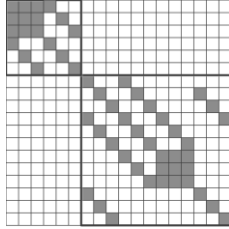


Fig. 8. Reordered Y matrix for the study case 2 (remains equal).

	n1	n2	n3	n4	n5	n2-1
n1	1	1	0	0	0	0
n2	1	1	0	0	0	1
n3	0	0	1	0	0	1
n4	0	0	0	2	2	0
n5	0	0	0	2	2	0
n2-1	0	1	1	0	0	1

Fig. 9. IM obtained for the study case 3.

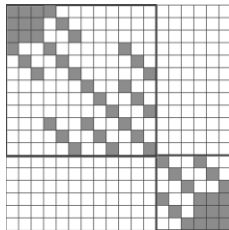


Fig. 10. Reordered Y matrix for the study case 3.

	n1	n2	n3	n2-1	n4	n5
n1	1	1	0	0	0	0
n2	1	1	0	1	0	0
n3	0	0	1	1	0	0
n2-1	0	1	1	1	0	0
n4	0	0	0	0	2	2
n5	0	0	0	0	2	2

Fig. 11. Reordered IM matrix for the study case 3.

	n1	n2	n3	n4	n5	n2-1
n1	1	1	0	0	0	0
n2	1	1	0	0	0	0
n3	0	0	2	0	0	2
n4	0	0	0	3	3	0
n5	0	0	0	3	3	0
n2-1	0	0	2	0	0	2

Fig. 12. IM matrix for the study case 4.

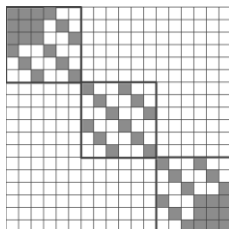


Fig. 13. Reordered Y matrix for the study case 4.

The next configuration happens when the recloser SW_1 (left) trips, thus separating the system in two islands. Then after execute the algorithm with this configuration, the IM obtained is as shown in Fig. 7. The suggested permutation remains equal the original organization of the Y matrix, since both islands have their components well grouped. The resulting Y Matrix is shown on Fig. 8.

However, in the third configuration the recloser SW_2 (right) trips and SW_1 closes. As result, the system is separated in two islands again but the components of the islands are separated as shown on Fig. 9. The node n2-1 is part of the island 1, but its location within the matrix is far from the other components of the island. As consequence the algorithm proposes the permutation: 0, 1, 2, 5, 3 and 4. Then, row and column 5 must be relocated into row and column 3. As result the Y matrix takes the form presented in Fig. 10.

As can be seen in this figure both islands are identified and grouped. Moreover, by checking the diagonal of the matrix IM after its reordering it is possible to locate the islands within the matrix as shown in Fig. 11. According to this figure, island 1 goes from nodes n_1 to n_2-1 while island 2, goes from nodes n_4 to n_5.

In the last configuration both reclosers are open creating 3 islands. In this case the IM matrix is as shown in Fig. 12. Again, because the island components are separated the algorithm suggests a permutation. This permutation is the same as in the case 3 due the distribution of the matrix. The new Y matrix after the permutation is shown on Fig. 13.

CONCLUSIONS

A simple algorithm for detecting and locating islands within sparse matrixes has been presented in this paper. This algorithm groups strongly connected elements, no matter the order of the matrix or if the elements of the island are separated.

The base of the algorithm is the representation of the system as incidence matrix. By using graph theory the grid can be represented as directed graph and then, translated into its adjacent representation. This allows to determinate which are the strongly connected elements; generating a new matrix called the Islands Matrix.

The information contained within the IM includes the location of the interconnected elements of each island, the location of each island, the permutation required for grouping the elements of each island and the number of islands. This information is the key for reordering the Y matrix and to perform several analyses.

Due its simplicity, this algorithm can be implemented using any programming language. The number of variables and expected results are described when presenting it on Fig. 3.

The presented study cases demonstrate that the algorithm can cover different configurations and will always detect the islands. In fact, due its iterative nature it is possible to use the algorithm in radial and meshed networks.

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