Application Of Sparsity Characteristics Of Power Systems To Ac Power-Flow Modelling And Simulation

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Abstract

Power flow is the basic tool for power system analysis which reveals the system operation in a steady-state mode for evaluation of the power system operations. Unfortunately, the accuracy, simulation time, computer storage size and convergence of any model used depend largely on the size of the bus admittance matrix of the system under study.

This paper, therefore, presents the application of power system sparsity characteristic to power-flow modelling and simulations to develop a model for storing the bus admittance matrix of power systems. In this paper a powerful MATLAB simulation algorithms have been developed that are capable of modeling large complex systems using sparsity characteristic of the power systems.

The validity of this proposed method using MATLAB 2009a is tested using a 5-bus, 6-bus and the standard IEEE 14-bus, 24-bus and 30-bus systems. The results are presented in graphical forms and discussed. The proposed method shows that as the system is increasing in size, the percentage of stored bus admittance elements decreases. Thus, an appreciable reduction in the computer memory required to store the bus admittance matrix and in turns reduces the overall simulation time.

Keywords: Power-flow, Steady-state, Sparsity characteristic, Admittance.

"1. Introduction"

As every nation approach an industrialized community, the rate at which the power demand increase is unpredictable if not properly analyzed [1, 2]. This calls for an accurate analysis and modelling of the steady state of the given system or network. As such, power-flow analysis is becoming the most important tool for evaluating power system performance under a steady-state operation in recent times [2, 3]. This evaluation of the system reveals the parameters of the system under a steady-state mode or operation. Power flow analysis is also an important tool during planning stages of new power system or addition to existing ones like adding new generator sites, meeting increase load demand and locating new transmission sites [4]. In power flow analysis, some power system parameters are important in determining the system performance. These parameters include voltage magnitude and angle at every bus of the system, real and reactive power injections at all the buses and power flows through interconnecting power channels, reactive power flows along the transmission lines, real and reactive power losses along the transmission lines and total losses [3]. In the study of electric power systems, several different researches have been carried out by different researchers using different methods. The most commonly used methods for power flow study are include Gauss-Seidel, Newton-Raphson and Fast decoupled. Among all these methods, Newton-Raphson is found to be the most widely deployed model in power systems applications [5, 2]. However, these conventional power flow algorithms are not efficient due to the challenges they encountered, which in most cases, results to divergence of the algorithms. These challenges include singularity of the Jacobian matrix most especially in Newton-Raphson method, large memory capacity for storing the elements of the Jacobian and the bus admittance matrix, convergence error or problem, high or large simulation time etc.

To combat the problems inherent in divergence algorithm, various modifications have been used by different researchers in the past [5]. This paper provides an excellent method of using sparsity characteristics of the power systems. Several different approaches have been applied to improve the numerical behaviour of Newton Raphson which is normally applied to a large scale power system. However, all these algorithms can still be improved if the sparsity characteristic of the system is explored.

All practical power systems have majority or larger percentage of their buses not connected through transmission lines [4]. This characteristic is explored in this paper such that only nonzero elements are stored and thereby resulting to savings in computer memory (the CPU time per iteration is made to be relatively small). The savings in computer memory is very important when dealing with large practical power systems to reduce the computation time [6] by reducing large memory required for the storage of the elements of bus admittance matrix.

Until recently, most industry effort and interest has been devoted to the algorithms for reducing the space occupied when storing the elements of Jacobian and bus admittance matrices by the computer memory. The efficient Newton-Raphson method for large power system has not been fully deployed to practical power system as the sparsity characteristic of the system has not been successfully used due to the repetitive solution of a large set of linear equations required in load flow problem which is one of the most time consuming parts of large power systems simulations. The major advantages of the application of this work are found in the areas such as existence of solution, uniqueness of solution convergence to the solution and speed of convergence.

In reference [2], fast Newton-Raphson method, through the application of preconditioning method in the Generalized Minimal Residual method (GMRES), called Newton-Krylov method is proposed. Validation of this proposed method showed that the convergence characteristics of the conventional Newton model are well preserved and the simulation time is reduced tremendously.

Seki, K in reference [5], in his work considered the analysis of no converge networks using load-flow program with complex number state variables. This work shows that since the Newton-Raphson power-flow equations is differential and does not satisfy Cauchy-Riemma conditions, it cannot be used to predict the voltage collapse behavior of any given system with complex number state variables. A new model based on the Gauss-Seidel iteration method which does not calculate the differential values of the power equations. However, the main roadblock is that, this method is found to be slower than the conventional Newton-Raphson model and it is difficult for the unstable voltage solutions of the network to be identified.

Gill, P. E. et al in reference [7] presented the reviews on applications of sparsity to optimization techniques in power systems. It is shown that, this method is of great importance, especially, in large practical power systems, to determine suitable finite-difference vector of Hessian matrix which is based on quasi-Newton approximation.

Sparse matrix solution in optimal direct current load-flow using Crout technique is proposed in reference [4]. This algorithm is based on the Crout Method for solving load-flow of sparsed power systems.

For decades, the commercially available softwares in use for the simulation of practical power systems include PSS/E, EuroStag, Simpow, CYME, PowerWorld and Neplan. In this paper, MATLAB 2009 is used for the simulation of the proposed model and the results are compared to validate the model. The data used for the validation of the proposed method are the line parameters for a 5-bus, 6-bus, 14-bus, 24-bus and 30-bus system.

Interconnections among power systems result in extremely large networks [2, 4]. This complexity in power system structure increases the computation and simulation times [6]. There are two major way of tackling the long simulation and computational times. Either by developing a more efficient sparsity computational model or by using a method called equivalence models which can be used to reduce the size of the given system to its thevenin equivalent model. This paper focuses on the first approach.

"2. Proposed Sparsity Technique"

In large power systems, each bus is connected to only a small number of other buses. Therefore, bus admittance matrix of a large power system is very sparse. This means that the bus admittance matrix will contain larger percentage of zeros as compared to the nonzero elements. This characteristic feature shows a considerable reduction in the storage handling of the computer which indicates a substantial improvement compared to the work reported in literature. This sparsity feature of Y_{bus} matrix also extends to Jacobian matrix. According to reference [8], "Sparsity can be simply defined to indicate the absence of certain problem interconnections". Mathematically, the sparsity of an $n \times n$ matrix is given by reference [4] as

$$\text{Sparsity} = \frac{Total\ no\ of\ \ zero\ elements}{n^2} \times 100\%$$

In a large power system such as the ones considered in this work, sparsity may be as high as 97%. Though Y_{bus} is sparse, Z_{bus} is full. This sparsity is employed in this work to ensure that only the non-zero elements are stored and the full characteristic of the original matrix is not lost.

"3. Model Validation"

The model proposed in this work is validated using the line parameters shown in the tables 1 to 6 below.

"Table 1. Line data for a 3-bus system"

Bus	Bus No.	R (pu)	X (pu)	B (pu)	Tap setting
1	2	0.02	0.04	0	1
1	3	0.01	0.03	0	1
2	3	0.0125	0.025	0	1

"Table 2. Line data for 5-bus system"

Bus	Bus No.	R (pu)	X (pu)	B (pu)	Tap setting
1	2	0.020	0.060	0.030	1.0
1	3	0.080	0.240	0.025	1.0
2	3	0.060	0.180	0.020	1.0
2	4	0.060	0.180	0.020	1.0
2	5	0.040	0.120	0.015	1.0
3	4	0.010	0.030	0.010	1.0
4	5	0.080	0.240	0.025	1.0

"Table 3. Line data for a 6-bus system"

Bus	Bus No.	R (pu)	X (pu)	B (pu)	Tap setting
1	4	0.035	0.225	0.0065	1.0
1	5	0.025	0.105	0.0045	1.0
1	6	0.040	0.215	0.0055	1.0
2	4	0.000	0.035	0.0000	1.0
3	5	0.000	0.042	0.0000	1.0
4	6	0.028	0.125	0.0035	1.0
5	6	0.026	0.175	0.0300	1.0

"Table 4. Line data for a 14-bus system"

Bus	Bus No.	R (pu)	X (pu)	B (pu)	Tap setting
1	2	0.01938	0.05917	0.0528	1.0
1	5	0.05403	0.22304	0.0492	1.0
2	3	0.04699	0.19797	0.0438	1.0
2	4	0.05811	0.17632	0.0374	1.0
2	5	0.05695	0.017388	0.0340	1.0
3	4	0.06701	0.17103	0.0346	1.0
4	5	0.01335	0.04211	0.0128	1.0
4	7	0.00	0.20912	0.00	0.978
4	9	0.00	0.55618	0.00	0.969
5	6	0.00	0.25202	0.00	0.932
6	11	0.09498	0.1989	0.00	1.0
6	12	0.12291	0.25581	0.00	1.0
6	13	0.06615	0.13027	0.00	1.0
7	8	0.00	0.17615	0.00	1.0
7	9	0.00	0.11001	0.00	1.0
8	10	0.03181	0.08450	0.00	1.0
8	14	0.12711	0.27038	0.00	1.0
10	11	0.08205	0.19207	0.00	1.0
12	13	0.22092	0.19988	0.00	1.0
13	14	0.17093	0.34802	0.00	1.0

"Table 5. Line data for a 24-bus system"

Bus	Bus No.	R (pu)	X (pu)	B (pu)	Tap setting
3	1	0.0006	0.0044	0.0295	1.0
4	5	0.0007	0.0050	0.0333	1.0
1	5	0.0023	0.0176	0.1176	1.0
5	8	0.0110	0.0828	0.5500	1.0
5	9	0.0054	0.0405	0.2669	1.0
5	10	0.0099	0.0745	0.4949	1.0
6	8	0.0077	0.0576	0.3830	1.0
2	8	0.0043	0.0317	0.2101	1.0
2	7	0.0012	0.0089	0.0589	1.0
7	24	0.0025	0.0186	0.1237	1.0
8	14	0.0054	0.0405	0.2691	1.0
8	10	0.0098	0.0742	0.4930	1.0
8	24	0.0020	0.0148	0.0982	1.0
9	10	0.0045	0.0340	0.2257	1.0
15	21	0.0122	0.0916	0.0689	1.0
10	17	0.0061	0.0461	0.3064	1.0
11	12	0.0010	0.0074	0.0491	1.0
12	14	0.0060	0.0455	0.3025	1.0
13	14	0.0036	0.0272	0.1807	1.0
16	19	0.0118	0.0887	0.5892	1.0
17	18	0.0002	0.0020	0.0098	1.0
17	23	0.0096	0.0721	0.4793	1.0
17	21	0.0032	0.0239	0.1589	1.0
19	20	0.0081	0.609	0.4046	1.0
20	22	0.0090	0.0680	0.4516	1.0
20	23	0.0038	0.0284	0.1886	1.0

"Table 6. Line data for a 30-bus system"

Bus	Bus No.	R (pu)	X (pu)	B (pu)	Tap setting
1	2	0.0192	0.0575	0.02640	1.0
1	3	0.0452	0.1852	0.02040	1.0
2	4	0.0570	0.1737	0.01840	1.0
3	4	0.0132	0.0379	0.00420	1.0
2	5	0.0472	0.1983	0.02090	1.0
2	6	0.0581	0.1763	0.01870	1.0
4	6	0.0119	0.0414	0.00450	1.0
5	7	0.0460	0.1160	0.01020	1.0
6	7	0.0267	0.0820	0.00850	1.0
6	8	0.0120	0.0420	0.00450	1.0
6	9	0.0	0.2080	0.0	0.978
6	10	0.0	0.5560	0.0	0.969
9	11	0.0	0.2080	0.0	1.0
9	10	0.0	0.1100	0.0	1.0
4	12	0.0	0.2560	0.0	0.932
12	13	0.0	0.1400	0.0	1.0

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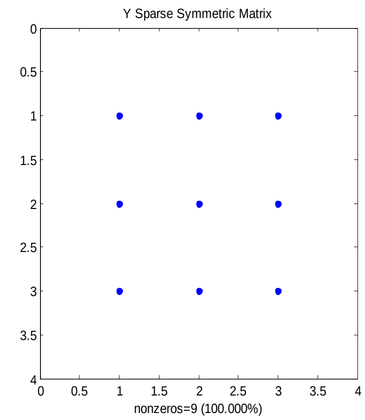
Bus	Bus No.	R (pu)	X (pu)	B (pu)	Tap setting
12	14	0.1231	0.2559	0.0	1.0
12	15	0.0662	0.1304	0.0	1.0
12	16	0.0945	0.1987	0.0	1.0
14	15	0.2210	0.9117	0.0	1.0
16	17	0.0824	0.1923	0.0	1.0
15	18	0.1073	0.2185	0.0	1.0
18	19	0.0639	0.1292	0.0	1.0
19	20	0.0340	0.0680	0.0	1.0
10	20	0.0936	0.2090	0.0	1.0
10	17	0.0324	0.0845	0.0	1.0
10	21	0.0348	0.0749	0.0	1.0
10	22	0.0727	0.1499	0.0	1.0
21	22	0.0116	0.0236	0.0	1.0
15	23	0.1000	0.2020	0.0	1.0
22	24	0.1150	0.1790	0.0	1.0
23	24	0.1320	0.2700	0.0	1.0
24	25	0.1885	0.3292	0.0	1.0
25	26	0.2544	0.3800	0.0	1.0
25	27	0.1093	0.2087	0.0	1.0
28	27	0.0	0.3960	0.0	0.968
27	29	0.2198	0.4153	0.0	1.0
27	30	0.3202	0.6027	0.0	1.0
29	30	0.2399	0.4533	0.0	1.0
8	28	0.0636	0.2000	0.0214	1.0
6	28	0.0169	0.0599	0.065	1.0

"4. Simulation Results and Discussion"

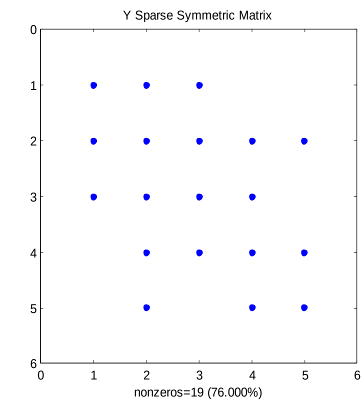
The results of the simulation, using the proposed technique, validated using the line data of tables 1 to 6, are presented in figures 1 to 6. These results can be summarised as shown in table 7.

"Table 7. Summary of the simulation results"

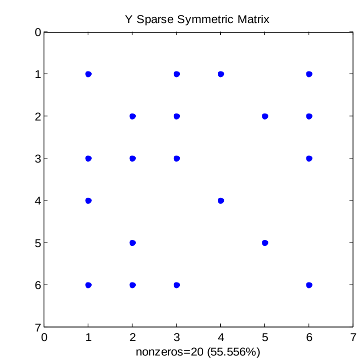
S/N	No of Buses	Percentage of stored elements
1	3	100.000
2	5	76.000
3	6	55.556
4	14	27.551
5	24	13.194
6	30	12.444



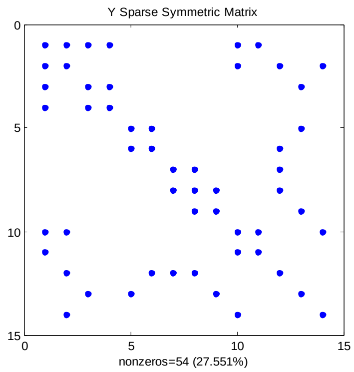
"Figure 1. Sparse matrix for a 3-bus system"



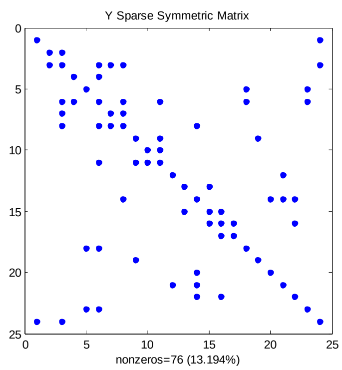
"**Figure 2. Sparse matrix for a 5-bus system"**



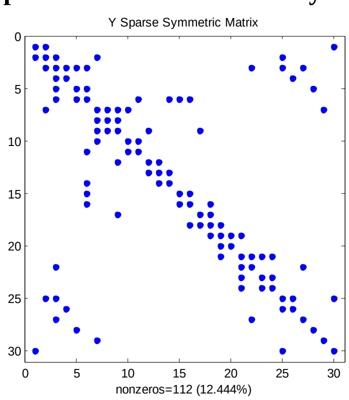
"Figure 3. Sparse matrix for a 6-bus system"



"**Figure 4. Sparse matrix for a 14-bus system"**



"Figure 5. Sparse matrix for a 24-bus system"



" Figure 6. Sparse matrix for a 30-bus system"

The output of the MATLAB simulation for various line data from different networks are displayed in figures 1 to 6 above.

"5. Conclusion"

Various aspects of the applications of sparsity technique in power systems have been extensively studied. An efficient algorithm for the modelling and simulation of the sparsity model has been presented and tested. The results of the simulation for various line parameters from different networks have been presented in both tabular and graphical forms as case studies. The result of the simulation revealed that the sparsity technique applications to large power systems reduces the computer memory required for the storage of the elements of the bus admittance matrix which consequently leads to savings in memory capability required for the simulation.

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