Comparison of power system flow analysis methods of IEEE 5-bus system

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ABSTRACT

Load flow analysis is a crucial tool used by electrical engineers for simulating the power system. It is aimed at examining the most possible way of operating and controlling a power system and the exchange of power flow within the power system. For the economic and optimal operation of power systems, the most essential task is to find the most feasible solution technique suitable and efficient for the study of power generation, transmission, and distribution. There are various power flow study solution techniques, and for some solution techniques, the simulation of the system can take a long time, which prevents the simulator from attaining a higher accuracy result for the power flow simulation due to the interrupting rise and fall in power demand from the consumer, which also affects the power generation as well. This paper discusses the comparison of various techniques used in load flow studies with the assistance of a small power system with five buses. The numerical solution techniques used are the fast decoupled load flow solution technique, the Gauss-Seidel solution technique, and the Newton-Raphson solution technique for a power flow study solution on an IEEE 5-bus using MATLAB/Simulink.

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1. INTRODUCTION

Power flow is the elementary steady-state examination of the power system which focuses on maintaining the balance between the total power generated by the generation system and the total number of loads connected to the system along with the losses occurring in the system. Due to the commercial evolution within the society, the facility system's unbroken increment conjointly causes the increment in the number of power flow equations to many thousands [1]. Due to this exponential increment in the number of equations, any numerical solution technique is insufficient to converge to an accurate solution. These equality restrictions are responsible for the modeling of nonlinear algebraic solutions which are solved using numerous numerical techniques. The efficiency of numerical solution techniques depends upon the accuracy of the simulation and the time required to carry out the simulation. Out of all the distinct solution techniques used for load flow solutions [2]. Fast decoupled load flow solution technique, Gauss-Seidel load flow solution technique, and Newton Raphson load flow solution technique are the most commonly used power flow solving techniques and each of these numerical techniques differs from each other based on the solution technique used to solve these nonlinear equations [3], [4]. The first and foremost step for executing the power flow study is the creation of Y bus admittance from the accessible data regarding transmission lines and transformers. The equations for any node in a power system with loads, generators, and buses with the help of the Y bus admittance matrix can be generally expressed as shown in (1) to (5).

$$I = Y_{BUS}V \quad (1)$$

The equation for the node can be expressed as shown in (2).

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j \; for \; i = 1,2,3, \dots . n \quad (2)$$

The sum of both real and reactive power delivered to the I^{th} bus can be expressed as:

$$P_i + jQ_i = VI^* \quad (3)$$

$$I_i = \frac{P_i + jQ_i}{V_i^*} \quad (4)$$

now substituting the value of I_i.

$$\frac{P_i + jQ_i}{V_i^*} = V_i \sum_{j=1}^{n} Y_{ij} - \sum_{j=1}^{n} Y_{ij}V_j \;, \; j \neq 1 \quad (5)$$

The mentioned (1) makes use of iterative strategies that are used to solve the power flow equations and the solution is then examined to extract all the necessary information and this information is further used in setting up the system in real-time [5]–[7]. Therefore, it is essential to check the overall styles used in the available solution techniques; Gauss-Seidel solution technique, Newton-Raphson solution technique, and fast decoupled load flow solution technique [8], [9].

The study offers a more comprehensive understanding of system behavior and performance under varying environmental conditions. Leveraging advanced optimization algorithms and intelligent control strategies, the model optimizes the power generation mix while ensuring grid stability and minimizing operational costs. By presenting a holistic framework that combines renewable integration, dynamic constraints handling, advanced optimization techniques, and resilience analysis, this study contributes significantly to the advancement of renewable energy integration in power system operation [10]. The major contributions of the proposed method are given:
- Evaluate the impact of energy integration on the IEEE 5-bus system's power flow and stability.
- Optimize power distribution to minimize transmission losses.
- Assess the economic viability and potential environmental impacts of the system.

2. METHOD

Load flow study is carried out using four different programs which are used in the program of fast decoupled, Gauss-Seidel, and Newton-Raphson solution techniques. The five different programs used to carry out the desired operations are Busout, Lineflow, Lfgauss, Lfnewton, Fdlf, and Lfybus. The functions carried out by these programs are:
- Busout: prints the solution of power flow carried out by the load flow analysis techniques on the screen.
- Lineflow: analyses and prints the results of the losses occurring at each transmission line.
- Lfybus: forms a bus admittance matrix from data provided by the user.
- Lfnewton: performs the power flow study using the Newton-Raphson solution technique.
- Lfgauss: performs the power flow study using the Gauss-Seidel solution technique.
- Fdlf: performs the power flow study using the fast decoupled solution technique.

The model designed for the simulation of the IEEE 5 bus in Simulink is shown in Figure 1.

3. MATHEMATICAL ANALYSIS

3.1. Gauss-Seidel solution technique

Gauss-Seidel numerical solution algorithm is an iterative numerical method that aims to solve a system of linear equations [11]–[14]. The Gauss-Seidel numerical solution technique solves these equations by repeatedly executing the equations again and again until the iteration answer is within a predefined acceptable range and is accurate enough to be accepted. It is a dependable load flow mechanism that can handle even the most complicated power systems [15]–[17]. The equation used for the repeated and regressive solution technique in this method is shown in (6).

$$V_k^{(i+1)} = \frac{1}{y_{kk}}\left(\frac{P_k - jQ_k}{(V_k^i)^*} - \sum_{n=1}^{N} Y_{kn} V_n^{(i)}\right) \quad (6)$$

The equation represents the updated value of the i^{th} component in the (k+1)th iteration, a_{ij}. Here $V_k^{(i+1)}$ denotes the elements of matrix A, and *n* is the dimension of the system. The method continues iterating until convergence is achieved, typically determined by a predefined tolerance or a maximum number of iterations. The Gauss-Seidel technique is known for its simplicity and suitability for solving sparse linear systems. Despite its advantages, convergence may not be guaranteed for all matrices, and careful consideration of the system's characteristics is necessary for successful application.

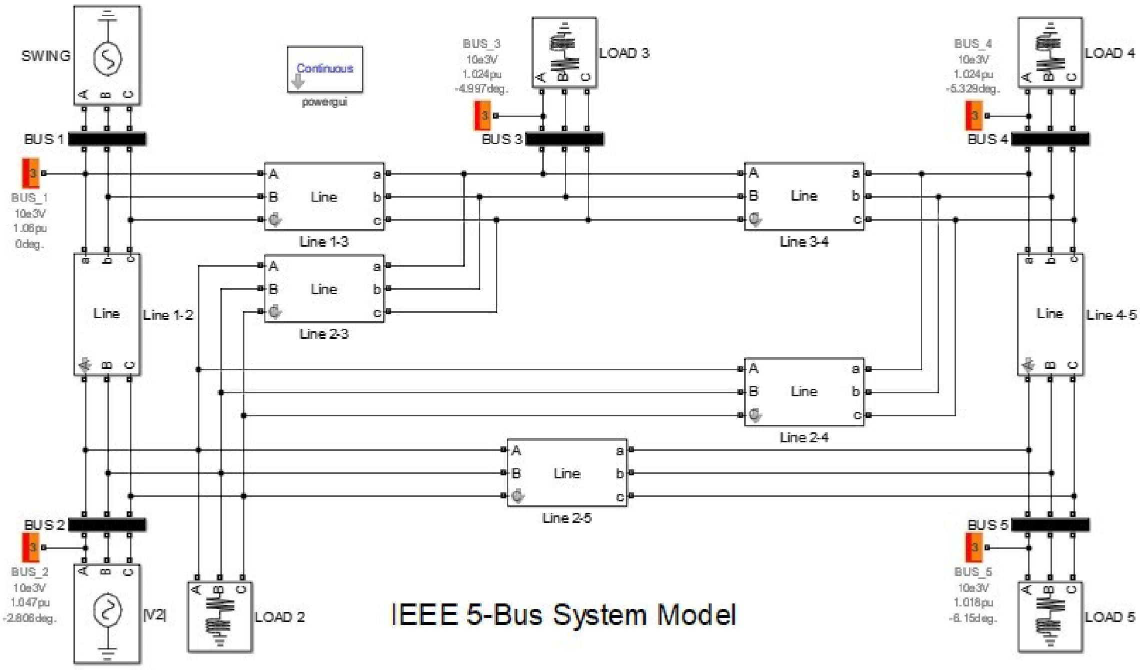

Figure 1. IEEE model in MATLAB/Simulink

3.2. IEEE 5 bus

The power system under study consists of five buses. Bus 1 is considered a reference bus while bus 2 is a generator, bus 3, 4, and 5 are all load buses. The type of bus, the rated of voltage, and the rated of power are shown in Table 1.

Table 1. IEEE data (source: IEEE 5 bus standard data)

Bus no.	Bus voltage (pu)	Generation		Load	
		MW	MVar	MW	MVar
1	1.06	0	0	0	0
2	1.0	40	30	20	10
3	1.0	0	0	45	15
4	1.0	0	0	40	5
5	1.0	0	0	60	10

3.3. Newton-Raphson solution technique

Newton-Raphson's solution is a widely accepted and applied algorithm for determining the solution of nonlinear equations on workstations or any computational system. Besides this, the application of the Newton-Raphson solution technique in real arithmetic operations requires at least two times larger memory storage references to perform the exact same amount of complex arithmetic calculations in the same amount of time [18], [19]. This algorithm is limited by the increased memory cycle time, as the computational system in which the simulation is taking place must repeatedly refer to the same memory references again and again until the solution is obtained, an algorithm that uses complex arithmetic rather than Newton-Raphson algorithm will be more efficient for the same number of operations [20].

3.4. Fast decoupled solution technique

The fast decoupled power flow approach is a very rapid as well as very efficient approach for solving the power flow scenarios. The speeds of the solution as well as the rarity of the solution are exploited in this approach. It is an evolved technique of the approach used in the Newton-Raphson formulated in polar coordinates with positive approximations which end up in a quick set of rules to remedy the energy flow [21]. This approach takes benefit of the belongings of the energy system in which, in MW, the flux voltage attitude and the flux voltage amplitude multivariate autoregressive (MVAR) are weakly combined. It can also be interpreted as, a small alternate in the amplitude of the bus voltage no longer having an effect on the real energy glide at the bus and in addition a small alternate in the section attitude of the bus voltage does. Sincerely no impacts on reactive power flow [22], [23]. This decoupling offers a totally simple, rapid, and dependable set of rules. As we know, the parsimony characteristic of the admittance matrix minimizes the reminiscence necessities of the computer and permits quicker calculations. The precision is similar to that of the Newton-Raphson approach.

4. RESULT AND DISCUSSION

In this study, we utilized three distinct solution techniques, namely Gauss-Seidel, Newton-Raphson, and fast decoupled, to analyze a power system. From the analysis, we determine the real and reactive power generation, load, line losses, and maximum power mismatch. The result for the power flow solution, line parameters, and line losses using the Newton-Raphson solution technique is shown in Figures 2 and 3. The result and program written for power flow solution, line parameters and line losses using fast decoupled solution technique are shown in Figures 4 and 5.

The presented Table 2 outlines the results obtained from three distinct power system solution techniques: Gauss-Seidel, Newton-Raphson, and fast decoupled. In terms of real power generation, the methods yielded slightly varying values, with Gauss-Seidel producing 169,496 MW, Newton-Raphson 169,575 MW, and fast decoupled 169,559 MW. The real load, representing the power consumed by the system, remained consistent across all three techniques at 165,000 MW. Real line losses, indicative of power dissipated during transmission, also exhibited minimal differences, with Gauss-Seidel, Newton-Raphson, and fast decoupled reporting 4,588 MW, 4,587 MW, and 4,587 MW, respectively. For reactive power aspects, there were nuanced distinctions. Reactive power generation values were 22,677 MVar, 22,430 MVar, and 22,567 MVar for Gauss-Seidel, Newton-Raphson, and fast decoupled, respectively. Reactive loads, representing the reactive power consumed by the system, were consistent at 40,000 MVar for all techniques. Reactive line losses, denoting the difference between reactive power generation and consumption in transmission, displayed marginal differences, with Gauss-Seidel reporting -17.417 MVar, Newton-Raphson -17.421 MVar, and fast decoupled -17.420 MVar. Furthermore, the analysis included a measure of convergence, Max. power mismatch, which gauges the effectiveness of each technique in reaching a balanced state. Gauss-Seidel recorded a value of 0.00095095, Newton-Raphson 0.000965758, and fast decoupled 0.000435626. Smaller values signify better convergence. In summary, the results underscore the subtle divergences among the three solution techniques in determining the operational parameters of the power system, with each approach presenting its unique strengths and precision in achieving a balanced and stable state. Figure 6 shows the comparison of Gauss-Seidel method, Newton-Raphson method, and fast decoupled methods.

Table 2. Comparison in Gauss-Seidel, Newton-Raphson, and fast decoupled for various parameters of load flow study

Parameter	Gauss-Seidel solution technique	Newton-Raphson solution technique	Fast decoupled solution technique
Real power generation	169,496 MW	169,575 MW	169,559 MW
Real load	165,000 MW	165,000 MW	165,000 MW
Real line loss	4,588 MW	4,587 MW	4,587 MW
Reactive power generation	22,677 MVar	22,430 MVar	22,567 MVar
Reactive load	40,000 MVar	40,000 MVar	40,000 MVar
Reactive line loss	-17.417 MVar	-17.421 MVar	-17.420 MVar
Max. power mismatch	0.00095095	0.000965758	0.000435626

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Power Flow Solution by Newton-Raphson Method
Maximum Power Mismatch = 0.000965758
No. of Iterations = 3

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.060	0.000	0.000	0.000	129.575	-7.570	0.000
2	1.047	-2.806	20.000	10.000	40.000	30.000	0.000
3	1.024	-4.997	45.000	15.000	0.000	0.000	0.000
4	1.024	-5.329	40.000	5.000	0.000	0.000	0.000
5	1.018	-6.150	60.000	10.000	0.000	0.000	0.000
Total			165.000	40.000	169.575	22.430	0.000

Figure 2. Results of load flow study using Newton-Raphson solution technique

Line Flow and Losses

--Line-- from	to	Power at bus & line flow MW	Mvar	MVA	--Line loss-- MW	Mvar	Transformer tap
1		129.575	-7.570	129.796			
	2	88.864	-8.579	89.277	1.410	-2.431	
	3	40.723	1.158	40.739	1.192	-1.855	
2		20.000	20.000	28.284			
	1	-87.453	6.149	87.669	1.410	-2.431	
	3	24.694	3.546	24.948	0.352	-3.238	
	4	27.936	2.962	28.093	0.441	-2.966	
	5	54.823	7.343	55.313	1.125	0.176	
3		-45.000	-15.000	47.434			
	1	-39.531	-3.014	39.646	1.192	-1.855	
	2	-24.343	-6.784	25.270	0.352	-3.238	
	4	18.874	-5.202	19.578	0.036	-1.990	
4		-40.000	-5.000	40.311			
	2	-27.495	-5.928	28.126	0.441	-2.966	
	3	-18.838	3.212	19.110	0.036	-1.990	
	5	6.333	-2.285	6.733	0.031	-5.118	
5		-60.000	-10.000	60.828			
	2	-53.698	-7.167	54.174	1.125	0.176	
	4	-6.302	-2.833	6.910	0.031	-5.118	
Total loss					4.587	-17.421	

Figure 3. Results showing line flow and losses using Newton-Raphson solution technique

Power Flow Solution by Fast Decoupled Method
Maximum Power Mismatch = 0.000435626
No. of Iterations = 9

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.060	0.000	0.000	0.000	129.559	-7.433	0.000
2	1.047	-2.807	20.000	10.000	40.000	30.000	0.000
3	1.024	-4.997	45.000	15.000	0.000	0.000	0.000
4	1.024	-5.329	40.000	5.000	0.000	0.000	0.000
5	1.018	-6.150	60.000	10.000	0.000	0.000	0.000
Total			165.000	40.000	169.559	22.567	0.000

Figure 4. Results of load flow study using fast decoupled solution technique

Line Flow and Losses

--Line-- from	to	Power at bus & line flow MW	Mvar	MVA	--Line loss-- MW	Mvar	Transformer tap
1		129.559	-7.433	129.772			
	2	88.867	-8.588	89.281	1.411	-2.431	
	3	40.724	1.158	40.741	1.192	-1.855	
2		20.000	20.000	28.284			
	1	-87.456	6.157	87.673	1.411	-2.431	
	3	24.695	3.548	24.949	0.352	-3.238	
	4	27.937	2.964	28.094	0.441	-2.965	
	5	54.825	7.347	55.316	1.125	0.176	
3		-45.000	-15.000	47.434			
	1	-39.532	-3.013	39.647	1.192	-1.855	
	2	-24.344	-6.785	25.272	0.352	-3.238	
	4	18.875	-5.200	19.578	0.036	-1.990	
4		-40.000	-5.000	40.311			
	2	-27.496	-5.929	28.128	0.441	-2.965	
	3	-18.840	3.210	19.111	0.036	-1.990	
	5	6.333	-2.284	6.733	0.031	-5.118	
5		-60.000	-10.000	60.828			
	2	-53.700	-7.171	54.177	1.125	0.176	
	4	-6.303	-2.833	6.910	0.031	-5.118	
Total loss					4.587	-17.420	

Figure 5. Results showing line flow and losses using a fast decoupled solution technique

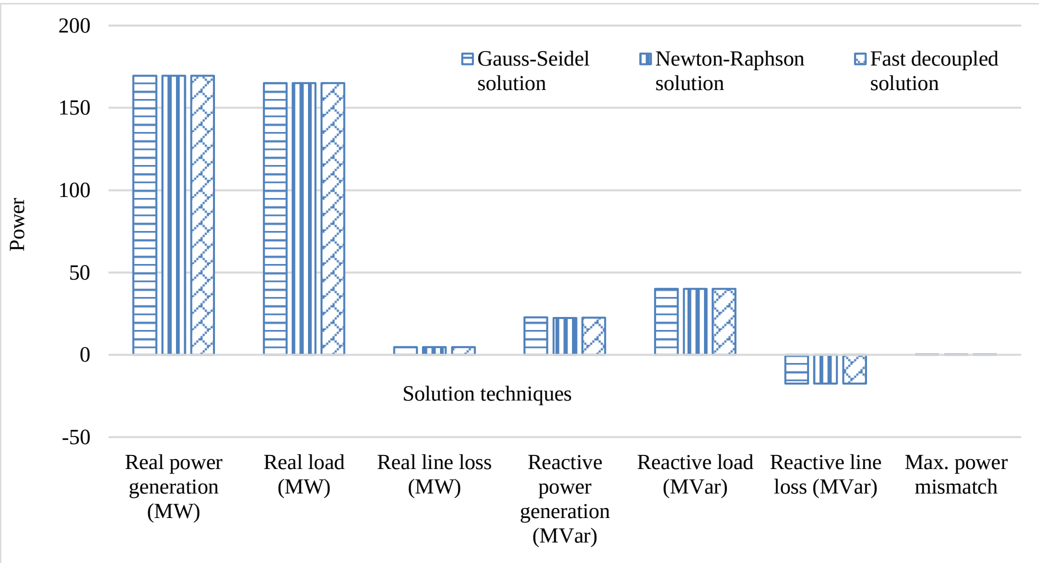

Figure 6. Results showing a comparison between solution techniques

Real power generation closely matching the real load is a key objective for power system stability and efficiency. The differences in real power generation among the three methods are minimal, indicating the effectiveness of all techniques in maintaining power balance. Accurate estimation and minimization of line losses are crucial for efficient power transmission [24], [25]. The slight differences in line losses among the techniques highlight their efficacy in managing power losses within the system. Maintaining a balance between reactive power generation and load is essential for ensuring voltage stability and system reliability. The results show minor variations in reactive power generation, demonstrating the robustness of the utilized techniques in achieving this balance. The maximum power mismatch represents the degree of convergence achieved by each solution technique. A smaller mismatch indicates better convergence, highlighting the computational efficiency and accuracy of the respective method. This comparative analysis provides valuable insights into the performance of Gauss-Seidel, Newton-Raphson, and fast decoupled solution techniques in power system analysis. These findings can guide power system engineers and researchers in selecting the most suitable approach for their specific applications, ultimately contributing to an optimized and reliable power infrastructure.

5. CONCLUSION

All the simulations of the load flow study were executed using MATLAB R2021b for a system of IEEE 5 buses. The tolerance value for all the solution techniques is 0.001, which conveys that all three iterative solution techniques have very high accuracy. The time taken by the Gauss-Seidel solution technique to complete the iterations is much larger than the time taken by both the Newton-Raphson solution technique and the fast-decoupled solution technique. The computation time for the Gauss-Seidel solution technique is much greater than that of the Newton-Raphson solution technique and the fast-decoupled solution technique due to the vast difference in the number of iterations taken by the Gauss-Seidel solution technique. The number of iterations taken by Gauss-Seidel is 38, while the number of iterations taken by Newton-Raphson is only 3, and the number of iterations taken by the fast decoupled solution technique is 9, which makes it faster than Gauss-Seidel but slower than Newton-Raphson. The Newton-Raphson and fast decoupled solution techniques take more time for computation and operation as a result of the high complexity of the Jacobian matrix used for every single iteration, but even after the high complexity of the Jacobian matrix. The convergence in the fast decoupled solution technique is faster due to the reduced number of iterations as compared to other numerical solution techniques. The maximum power mismatch in the Gauss-Seidel solution technique is less than the power mismatch in the Newton-Raphson solution technique. Hence, it is conclusive that the Newton-Raphson solution technique and the fast decoupled solution technique are reliable for large systems as they converge fast and have high accuracy with a very small computation time, whereas the Gauss-Seidel solution technique has a slow computation rate but is very accurate for load flow studies of small systems.

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