A comparative analysis of hybrid of traditional load flow methods for IEEE distributed power generation networks

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ABSTRACT

Analyzing power flow or load flow is crucial for planning, operating, maintaining, and controlling electrical power systems. Two traditional power flow methods namely the Newton-Raphson (NR) method are known for their accuracy and robustness nevertheless high computational intensity, and the fast decoupled load flow (FD) method, is valued for its computational efficiency and speed, however, generating less accurate data. This research aims to develop a hybrid load flow technique that integrates both strengths, achieving higher accuracy and faster convergence. The validation processes are based on several IEEE standard bus systems, including the 3-bus, 9-bus, 14-bus, and 30-bus systems. These systems, with different bus types and interconnections, represent real-world operations and help generate comprehensive data on iteration count, execution time, and the accuracy of the output data results. A new hybrid method generated from this research work compared to traditional load flow methods, provides a substantially well-balanced number of iteration counts, the fastest execution times, improved by 41.55%, and produces a similar accuracy of the data set. These improvements make the hybrid method highly advantageous in practical real-time applications and large-scale systems where both accuracy and speed are critical.

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1. INTRODUCTION

The power flow analysis, also known as load flow analysis plays a crucial role in the comprehensive management of power systems, encompassing planning, operation, maintenance, and control [1]. It is significance is vital in the planning stage, where load flow studies are conducted to assess the loading conditions of specific power system components, identifying the system state of underloading or overloading. The results of these studies unfold major investment decisions, ensuring the efficient operation of generators work at their optimal points [1], [2]. Traditionally, load flow studies were conducted using network analyzers. These analyzers were analog, scaled-down models of power systems, incorporating resistances, reactance, capacitances, autotransformers, transformers, loads, and generators [3]. In load flow studies, power flow is traced from the sending to the receiving end of transmission lines involving the solution of nonlinear power flow equations through iterative methods such as Gauss-Seidel, Newton-Raphson (NR), and fast-decoupled (FD) power flow [4]. The nonlinear power flow equations must be solved iteratively to determine voltage drops, magnitudes, phase angles at each bus, and real and reactive powers in all branches [5]. In addition to its role in planning and operational considerations, load flow analysis has added a significant role as a precursor to transient stability and contingency tests in power systems [6]. These analyses serve as proactive measures to assess and ensure the resilience and reliability of the system under dynamic conditions and unexpected events. One noteworthy outcome of load flow investigations is the potential identification of overloaded connections or transformers, critical insights that contribute to the overall health and efficiency of the power network [6], [7]. Load flow analysis, the method employed in this research, revolves around solving nodal power balancing equations. Given the inherently nonlinear nature of these equations, the industry widely relies on iterative approaches for their resolution [4]. Notable methods include Gauss-Seidel, NR, and FD power flow, each chosen based on specific considerations [7].

The Gauss-Seidel method, although slower than its counterparts, is favored for its stability and comprehensibility. This approach involves iteratively substituting nodal equations into each other. While not considered the most sophisticated load flow technique, Gauss-Seidel was extensively utilized until the early 1970s due to its simplicity and ease of understanding [1], [3]. Its convergence is monotonic, and although it may not offer the utmost precision, it remains a valuable tool in load flow analysis. The NR method emerges as the most efficient algorithm for load flow analysis. This method is based on the formal application of a well-established approach and tackles simultaneous nonlinear equations with a fundamental algorithm that involves no approximations. Its efficiency makes it a preferred choice in solving complex power flow problems, especially in scenarios where precision and computational speed are paramount [8]. The FD power flow technique represents a swift and efficient solution to power flow problems. Leveraging both speed and sparsity, this method is an extension of the NR technique, operating in polar coordinates with specific approximations. The result is a rapid algorithm for power flow analysis, demonstrating the industry’s commitment to continuously improving and optimizing the methodologies used in managing power systems [9]. This research aims to develop a new hybrid load flow analysis method that combines the supremacy of both the NR and the FD, consequently able to improve the number of iteration counts, and execution times, and produce the most accurate data set for selected IEEE standard bus systems.

2. METHOD

This section provides a detailed overview of the research’s procedures and structures. The main simulation tool used for creating and testing all generated algorithms is MATLAB software. Three major load flow techniques will be used in this research work, namely the NR, FD, and a new proposed hybrid strategy of load flow analysis called the NR-FD method.

2.1. Newton-Raphson method

The NR method is a numerical process that finds the roots of any given real-valued function [10]. It is predicated on the idea of using the function’s tangent line at a specific location to approximate a function’s root. The process starts with a preliminary estimate of the root and keeps refining it until the required level of precision is attained. For any type of bus, the current equation in terms of its admittance matrix (Y_{Bus}) is expressed as:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad (1)$$

where I_i, Y_{ij}, V_j are defined as bus current, admittance between busses i and j, and bus voltage j respectively. By expressing (1) in polar form as given by (2).

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j \quad (2)$$

Therefore, the complex power of the bus i is given as follows:

$$P_i - jQ_i = V_i^* I_i \quad (3)$$

where P_i, jQ_i both are defined as an active power on the bus $i,$ and reactive power on the bus i respectively. Substituting I_i from (2) into (3) and separating both the real and imaginary parts gives [11].

$$P_i = \sum_{j=1}^{n} |V_i||V_j||V_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (4)$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (5)$$

The (4) and (5) constitute nonlinear algebraic equations in terms of independent variables that, for all cases, are found in per unit $(p.u)$ with angles given in radians. The elements of J are obtained from partial derivatives of (4) and (5) are evaluated based on the values of $\Delta\delta_{ik}$ and $\Delta|V_{ik}|$ [12], given;

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{6}$$

the terms $\Delta P_k$and ΔQ_k are defined as the difference (ε) between the specified values for each iteration based on (4) and (5) respectively. The new complex voltages in the knots are given by:

$$\delta_i^{(k+1)} = \delta_i^k + \Delta\delta_i^k \tag{7}$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^k\right| + \Delta\left|V_i^k\right| \tag{8}$$

where both $\delta_i^{(k+1)}$ and $V_i^{(k+1)}$ are defined as the angle result of i for the iteration of $k+1$ and voltage result of i for the iteration $k+1$ respectively.

2.2. Fast decouple method

Alternatively, power flow equations in an electrical power system could be solved using another technique called FD load flow analysis. This method allows for the ignoring of resistance in the calculations by assuming that the reactance of gearbox lines substantially exceeds their resistances, hence simplifying the equations. It further assumes that the admittance matrix's off-diagonal members are far smaller than its diagonal elements, allowing these off-diagonal parts to be left out of the (9) [13].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{9}$$

A change in the voltage magnitude $|V|$ in a bus, mainly affects the reactive power flow in the transmission lines and relatively leaves the real power flow unchanged. Given,

$$\frac{\Delta P}{V_i} = -B'\Delta\delta \tag{10}$$

$$\frac{\Delta Q}{V_i} = -B''\Delta|V| \tag{11}$$

where B' and B'' are the imaginary part of Y_{bus} and in both cases, they are constant matrices, so they are built and factor themselves only once. With a simplified admittance matrix, the load flow equations can be solved effectively under these assumptions. While the solution of a FD approach is often more rapid and effective than the complete NR method, precision may be somewhat compromised, particularly in systems with high loads or weak connections.

2.3. Hybrid method

The hybrid of the NR and FD methods aims to complement the advantages and disadvantages of both approaches consequently improving the efficiency and accuracy of load flow analysis in electrical power systems. The NR method is renowned for its high accuracy and fast convergence, making it suitable for solving nonlinear systems of equations that arise in power flow analysis. On the other hand, the FD method is known for its speed and efficiency in solving power flow problems, especially in systems with a significant number of transmission lines. The integration of two traditional methods took place in which the algorithm from the FD technique is implemented to quickly obtain an initial condition value and then the solution is further refined using the NR method to achieve higher accuracy. This hybrid approach could significantly reduce the computational time required for load flow analysis while maintaining the accuracy of the required results. The flowchart of the proposed hybrid method in this research work is illustrated as shown in Figure 1.

3. IEEE BUS SYSTEM

The IEEE bus model systems are used widely by researchers to examine the effectiveness of new algorithms and concepts in analyzing the load flow in distributed power generation networks [14]-[16].

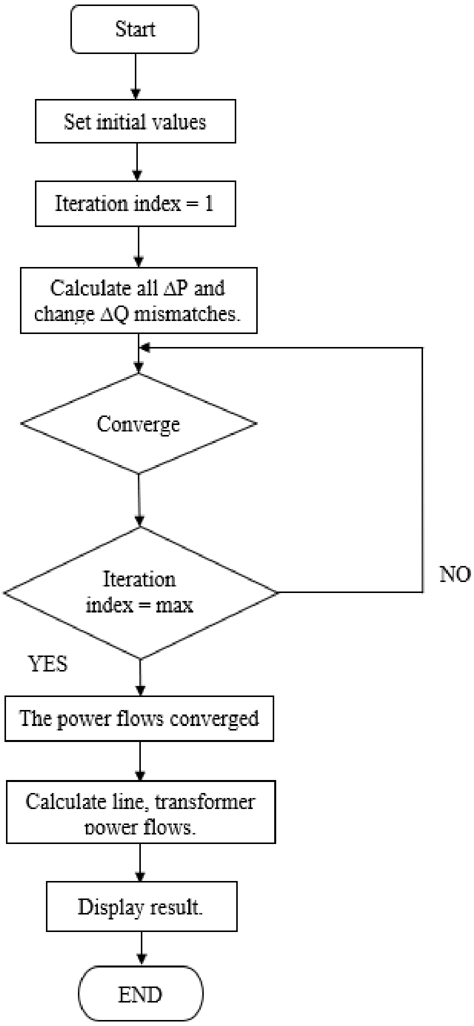

Figure 1. Flowchart of proposed hybrid method in load flow analysis

3.1. IEEE 3-bus system

The most common IEEE bus system used is based on the 3-bus system as shown in Figure 2. It features two generator sources, labeled 1 and 2, connected to a common bus, depicted by a horizontal line. These buses serve as a central connection point for multiple circuits connection. The arrows labeled at bus 3 indicate electrical loads such as residential, commercial, or industrial users connected to the bus.

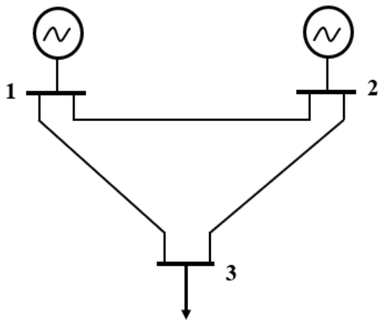

Figure 2. Single-line diagram for IEEE 3-bus system [17]

3.2. IEEE 9-bus system

Figure 3 shows a standardized IEEE 9-bus model used to represent the network of generators, loads, and buses in electrical power systems. These generators at nodes 1, 2, and 3 are connected to a network of buses, labeled 4, 5, 6, 7, 8, and 9, where each bus acts as a node for voltage level control and power distribution.

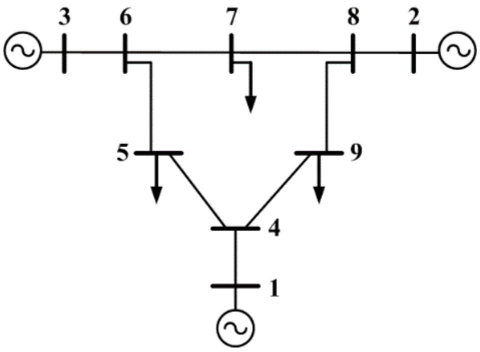

Figure 3. Single line IEEE 9-bus system [18]

3.3. IEEE 14-bus system

An IEEE 14-bus system model as illustrated in Figure 4, consists of multiple generators, marked with 'G', located at buses 1 and 2 respectively. Synchronous compensators, marked with 'C', are present on buses 3, 6, and 8, providing voltage support and reactive power compensation to maintain the system stability and improve power quality.

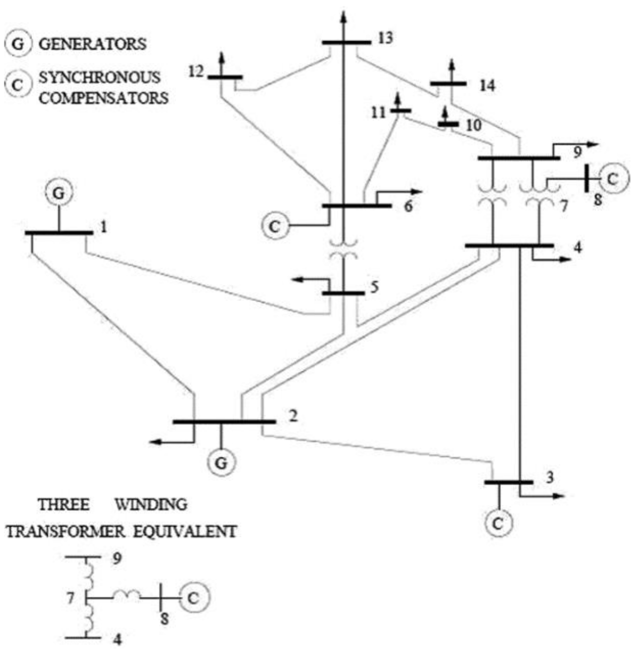

Figure 4. Single line IEEE 14-bus system [19]

3.4. IEEE 30-bus system

Figure 5 shows a single-line diagram of the IEEE 30-bus system that serves as a benchmark for load flow studies [20]–[22]. The system includes multiple generators, and also various loads, depicted by arrows which represent points of power consumption.

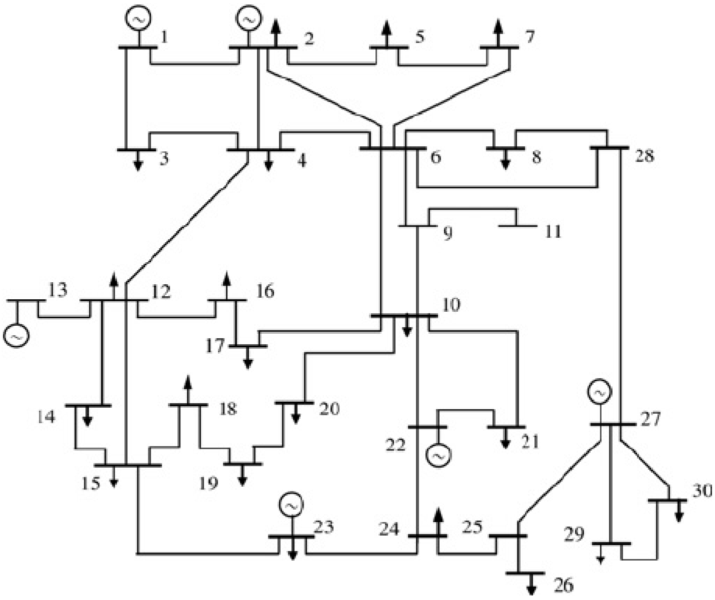

Figure 5. Single-line IEEE 30-bus system [20]

4. RESULTS AND DISCUSSION

This section presents the outcomes of the research work and simultaneously provides a comprehensive analysis based on the generated results. The number of iterations required, the duration of execution time, and data accuracy become the main indicators in analyzing the overall load flow technique performances [23]–[25].

4.1. Number of iterations and execution time

Table 1 presents the output data from the selected load flow methods, namely NR, FD, and hybrid (H) methods. Both NR and hybrid methods, required only 3 iterations, in contrast, the FD method needed 9 iterations to converge, slightly higher than the NR and hybrid methods.

Table 1. IEEE 3-bus system

Method	Number of iterations	Execution time (s)			
		First	Second	Third	Average
NR	3	0.0389	0.0872	0.0517	0.0593
FD	9	0.0096	0.0048	0.0052	0.0065
Hybrid	3	0.0617	0.0165	0.0086	0.0289

The FD method demonstrated the fastest average execution time at 0.0065 seconds, attributed to the simplifications in the power flow equations that were able to reduce the computational load per iteration. The hybrid method had an average execution time of 0.0289 seconds, striking a balance between the NR and FD methods by offering a moderate execution time that benefits from the strengths of both approaches.

Meanwhile, Table 2 presents the results derived from the IEEE 9-bus system, both the NR and hybrid methods converging in just 9 iterations. In contrast, the FD method needed 23 iterations to reach a solution. Moreover, the hybrid method had the shortest average execution time at 0.0078 seconds, making it the fastest among the three methods. Table 3 presents the findings based on the IEEE 14-bus system.

Table 2. IEEE 9-bus system

Method	Number of iterations	Execution time (s)			
		First	Second	Third	Average
NR	9	0.0144	0.0318	0.0070	0.0177
FD	23	0.0841	0.0234	0.0106	0.0394
Hybrid	9	0.0115	0.0071	0.0049	0.0078

Table 3. IEEE 14-bus system

Method	Number of iterations	Execution time (s)			
		First	Second	Third	Average
NR	9	0.0084	0.0263	0.0135	0.0161
FD	26	0.0118	0.0096	0.0118	0.0111
Hybrid	9	0.0075	0.0101	0.0091	0.0089

The NR and hybrid methods both require 9 iterations to converge, significantly fewer than the 26 iterations needed by the FD method, indicating quicker convergence. In terms of execution time, the hybrid method consistently shows the fastest average execution time at 0.0089 seconds, followed by the FD method at 0.0111 seconds, while the NR method has the longest average execution time at 0.0161 seconds. Despite the NR and hybrid methods having the same number of iterations, the hybrid method executes faster, indicating a more efficient computational approach. Table 4 tabulated the findings from the IEEE 30-bus system.

The NR method needed only 4 iterations but had slightly longer execution times with an average of 0.0104 seconds. The FD method required 15 iterations, with more stable and quicker times averaging 0.0118 seconds. The hybrid method also required just 4 iterations and had the fastest execution times, averaging 0.0092 seconds, combining efficiency in iterations and speed.

Table 4. IEEE 30-bus system

Method	Number of iterations	Execution time (s)			
		First	Second	Third	Average
NR	4	0.0145	0.0078	0.0089	0.0104
FD	15	0.0126	0.0116	0.0112	0.0118
Hybrid	4	0.0110	0.0091	0.0075	0.0092

4.2. Data accuracy

Table 5 shows the output result based on the IEEE 3-bus system for total generation and total line losses for all three methods namely NR, FD, and hybrid (NR FD). These results are taken based on input values provided by the selected bus systems. The hybrid method, which incorporates aspects of both the NR and FD methods, matches the accuracy of the NR method. This consistency in output indicates that the hybrid method effectively combines the strengths of its components to achieve high accuracy. Meanwhile, Table 6 shows the output result from the IEEE 9-bus system for total generation and the total line losses for all three designated methods.

Table 5. Power generation based on IEEE 3-bus system

Method	Total generation		Total line losses	
	Real (MW)	Reactive (Mvar)	Real (MW)	Reactive (Mvar)
NR	407.563	184.589	12.367	29.195
FD	407.542	184.687	12.366	29.194
Hybrid	407.563	184.589	12.367	29.195

Table 6. Power generation based on IEEE 9-bus system

Method	Total generation		Total line losses	
	Real (MW)	Reactive (Mvar)	Real (MW)	Reactive (Mvar)
NR	10.734	-215.289	8.254	-215.289
FD	10.613	-217.437	8.226	-217.453
Hybrid	10.734	-215.289	8.254	-215.289

In terms of real power generation, both the NR and hybrid methods produce an identical output of 10.734 MW, which is slightly higher than the 10.613 MW generated by the FD method. For reactive power, the NR and hybrid methods again show the same value of -215.289 Mvar, which is less negative than the -217.437 Mvar produced by the FD method, indicating better efficiency in maintaining reactive power levels. When examining total line losses, the real power losses are the same for both NR and hybrid methods at 8.254 MW, marginally higher than the 8.226 MW generated from the FD method. Regarding reactive power losses, the NR and hybrid methods show identical values of -215.289 Mvar, which is slightly less negative than the -217.453 Mvar for the FD method. Meanwhile, Table 7 shows the output result from the IEEE 14 bus system for total generation and the total line losses for all three methods. Both the NR as well as hybrid methods produce 52.499 MW, while the FD method generates slightly more at 52.516 MW of active power generation.

Table 7. Power generation based on IEEE 14-bus system

Method	Total generation		Total line losses	
	Real (MW)	Reactive (Mvar)	Real (MW)	Reactive (Mvar)
NR	52.499	120.509	12.515	25.191
FD	52.516	120.633	12.515	25.192
Hybrid	52.499	120.509	12.515	25.191

For total reactive power generation, the NR and hybrid methods again show identical results at 120.509 Mvar, slightly less than the 120.633 Mvar generated by the FD method. All three methods exhibit identical total real power line losses at 12.515 MW. However, for reactive power losses, the NR and hybrid methods show the same value of 25.191 Mvar, while the FD method shows a slightly higher loss at 25.192 Mvar. Table 8 shows the output result from the IEEE 30 bus system for total generation and total line losses for all 3 methods. All three methods exhibit nearly identical performance in terms of total generation and total line losses. Specifically, for total real power generation, both the NR and hybrid methods report 301.037 MW, while the FD method shows a marginally lower value of 301.036 MW. For reactive power generation, the NR and hybrid methods both record 124.342 Mvar, with the FD method slightly higher at 124.343 Mvar. In terms of total line losses, all methods show identical real power losses of 17.637 MW. However, there is a minor variation in reactive power losses, where the NR and Hybrid methods both indicate 21.442 Mvar, while the FD method registers a slightly higher loss of 21.443 Mvar.

Table 8. Power generation based on IEEE 30-bus system

Method	Total generation		Total line losses	
	Real (MW)	Reactive (Mvar)	Real (MW)	Reactive (Mvar)
NR	301.037	124.342	17.637	21.442
FD	301.036	124.343	17.637	21.443
Hybrid	301.037	124.342	17.637	21.442

4.3. Overall buses comparison

Both Figures 6 and 7 show the comparison analysis between the number of iterations and average execution time for each method in individual bus systems respectively. The NR method is highly efficient in terms of iteration count, its complex computations result in a longer execution time. The FD method, although requiring more number of iterations process, is the fastest in terms of execution time due to its less intensive computations per iteration. The hybrid method offers a compromise, achieving a low iteration count like the NR method but with a more favorable execution time, effectively balancing the computational load. This comprehensive comparison highlights the trade-offs between iteration efficiency and computational speed among the three methods, providing valuable insights for selecting the appropriate method based on specific computational requirements and constraints.

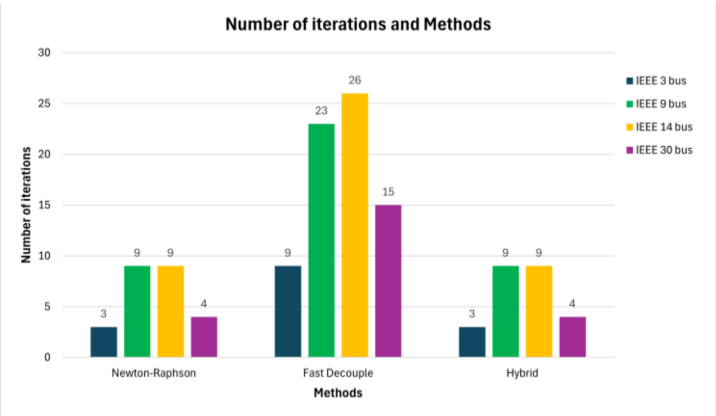

Figure 6. Comparison of the number of iterations and methods for each bus system

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Figure 7. Comparison of average execution time and methods for each bus system

Figure 8 shows the comparison between the accuracy of output results for each method. The NR and Hybrid methods provide identical results in both total power generations indicating a consistency in their performance. On the other hand, the FD method shows a slight variance in total generation results. Therefore, the NR and hybrid methods generate more efficient results due to their lower reactive power losses, making them preferable in terms of minimizing losses while maintaining adequate power generation.

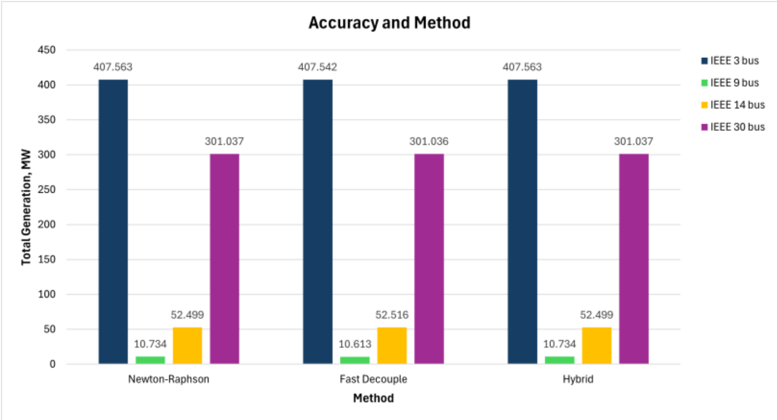

Figure 8. Comparison of accuracy and methods for each bus system

5. CONCLUSION

A comparative analysis of the selected load flow techniques, namely NR, FD, and hybrid methods based on the IEEE 3-bus, 9-bus, 14-bus, and 30-bus model systems, has been carried out in this research work. The NR method consistently provides precise results for all bus system models by iteratively refining the solutions using the internal function’s derivative. However, it requires a good initial presumption and is computationally complex. In contrast, by simplifying load flow equations into smaller parts, FD reduces complexity and speeds up the solution process, making it effective for larger network systems. The proposed hybrid method is based on the merging mechanism of traditional methods, where it begins with NR for an initial approximation and then refines it using FD. This approach balances both the execution speed and the data accuracy, making it suitable for various sizes of network systems. In conclusion, in comparison with both NR and FD methods, the proposed hybrid method provides a substantially well-balanced number of iterations counts and the fastest execution times, improved by 41.55%. The hybrid method’s efficiency and balance between accuracy and execution speed make it a promising tool for both real power grids and smart grids. By enabling faster load flow analysis, it can support real-time decision-making, enhance grid stability, and improve the integration of renewable energy and distributed resources. In smart grid applications, it contributes to optimizing energy distribution, demand response, and fault management, making it an essential tool for modernizing and enhancing grid operations.

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AUTHOR CONTRIBUTIONS STATEMENT

All authors have contributed to the study conception and design.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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