Proceedings of the 2022 Sustainable Research and Innovation Conference
JKUAT Main Campus, Kenya
5 - 6 October, 2022

Comparison of Software Packages for Unbalanced Load Flow Analysis: ETAP Versus PSCAD

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***Abstract*—**Power systems analysis also called load flow analysis is a very crucial aspect of power systems as it helps in enabling the effective planning and operation of the power system. The prime objective of load flow analysis is to ensure that the power generated at generating units is supplied to consumer load centers in a stable, economical, and reliable manner. Several methods have been developed for load flow calculations, the most common of these being the Newton-Raphson method, the Gauss-Seidel method, and the Fast-Decoupled method. To make power systems analysis easier and more convenient, several software packages have been developed making use of one or more of the mentioned methods. Each of these software packages has its error margin in load flow calculation. The objective of this paper is to compare the efficacy of two software; Electrical Transient and Analysis Program (ETAP), and Power System Computer-Aided Design (PSCAD) in unbalanced load flow analysis. Three IEEE test feeders are used; the IEEE 4 node, 13 node, and 34 node test feeders. Unbalanced load flow analysis of the test networks is done using ETAP and PSCAD, and the results obtained are compared with benchmarked results. For The 4 node and 13 node test networks, it is observed that the resulting node voltages with ETAP agree closer with published results compared to those obtained with PSCAD. In the case of the 34 node test feeder, the results obtained using PSCAD are better than those obtained with ETAP. To validate the overall efficacy of one software for unbalanced load flow analysis over the other, a larger number of unbalanced networks need to be analyzed with both tools and the results compared against benchmarked results.

Keywords— ETAP, PSCAD, Unbalanced load flow, Distribution network, Power systems analysis

I. INTRODUCTION

In power system, active and reactive power flow from the generating units to the consumption units and this flow of power is what is referred to as load flow, also called power flow. Load flow or power flow analysis/study is a crucial exercise in a power system as its target is to determine the current flow, bus voltages, and the real and reactive power flow in the network. This enables proper upfront planning and operation of the power network while taking into account hypothetical situations. Long ago, load flow analysis was done using specialized analog computers referred to as network analyzers, but with the development of high-speed digital computers, these network analyzers have been replaced, though still been used in initial planning [1].

Numerous software packages have been developed to perform load flow analysis. Some of these software packages are; ETAP, MATLAB, PowerWorld, PSCAD, PandaPower, and Digsilent, among others. Numerous researches have been done to compare the performance of software packages in load flow analysis of standard test networks such as the IEEE test feeders. IEEE test networks are well-known benchmarked networks that were first introduced by W. H. Kerstinq in 1991 to provide a common set of data to be utilized by program developers and users to validate the effectiveness of their solutions [2]

For example, in [3], the authors compared the performances of MATPOWER, PowerWorld, and PandaPower in the load flow analysis of the IEEE 9 bus and 14 bus test networks, and compared the obtained results with published standard results. The authors observed that the PowerWorld performed better for the IEEE 9 bus and MATPOWER performed better in the case of the 14 bus network. In [4], the performance of the Power Tool Analysis Toolbox (PSAT) and the ETAP for the load flow analysis of an 11 bus power system was done. It was found that the bus voltages obtained using PSAT deviated from the expected by 0.663%, while those obtained by ETAP deviated by 0.562%. The performance of PSD-BPA designed by China Electric Power Research Institute and PSS/NETOMAC developed by SIEMENS in load flow analysis is compared in [5]. It is observed that the computation results from both simulation tools are the same. In [6], the use of power system analysis tools such as NEPLAN, PSAT, MATPOWER, and PowerWorld for load flow analysis of the IEEE 9 bus and 14 bus systems was performed. The results obtained showed that all simulation tools achieved fairly accurate results for bus

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voltages as well as phase angles. The open-source tools, PSAT, and MATPOWER converged quickly with lesser iterations. The work in [7] was focused on comparing the performances of DIgSILENT PowerFactory, NEPLAN, SIMPOW, and PowerWorld which are commercial software against pandapower, PyPSA, and MATPOWER which are non-commercial for the load flow analysis of a 9 bus system with high penetration of wind power. The results obtained showed bus voltage deviations of less that 5% of the espected for all simulated wind power generation scenario. It was deduced that non-commercial software tools are an effective alternative for power system analysis with renewable energy integration. It should be noted that these related works cited compared these power system analysis tools for balanced power flow analysis.

This paper aims to compare the efficacy of two software packages, that is, ETAP, and PSCAD/EMTDC for unbalanced load flow analysis. Unbalanced load flow analysis is crucial for low voltage systems because it examines the asymmetrical traits linked to unbalanced components. Therefore, it is crucial to find an effective solution to the unbalanced load flow problem. The reason why this study performed. Three standard IEEE test distribution networks are used; the IEEE 4 node unbalanced network with stepdown transformer, the IEEE 13 node test feeder, and the IEEE 34 node test feeder.

II. METHODOLOGY

A. Study Networks

In this work, three standard IEEE test distribution networks are used; the IEEE 4 node test feeder, the IEEE 13 node test feeder, and the IEEE 34 node test feeder.

a. The IEEE 4 node test feeder: It is a 4 node distribution network with an inline transformer and a load as shown in Fig. 1 below.

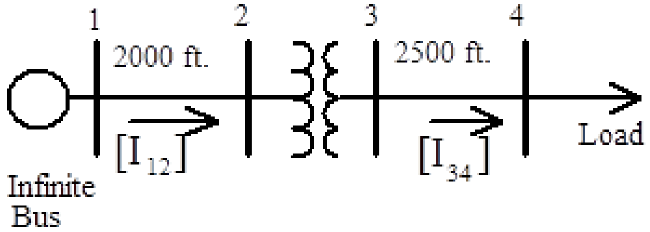

Fig. 1. The IEEE 4 Node test feeder [8]

The inline transformer of the network could be simulated to work as a step-up mode or stepdown mode. Also, for each of the modes of operation of the inline transformer, the load could be used as balanced or unbalanced. That, therefore, means that the IEEE 4 node test feeder can assume four configurations as follows;

- A balanced network with its transformer operating in the stepdown mode
- A balanced network with its transformer operating in step-up mode
- An unbalanced network with its transformer operating in the stepdown mode
- An unbalanced network with its transformer operating in step-up mode

In this research, load flow of the network will be performed in the third configuration; that is, an unbalanced network with its transformer operating in the step-down mode.

b. IEEE 13 node test feeder: It is a very small, but heavily loaded distribution network at a three-phase voltage of 4.16kV, and it comprises both overhead and underground lines with a variety of phasing [9]. Its single-line diagram is shown in Fig. 2.

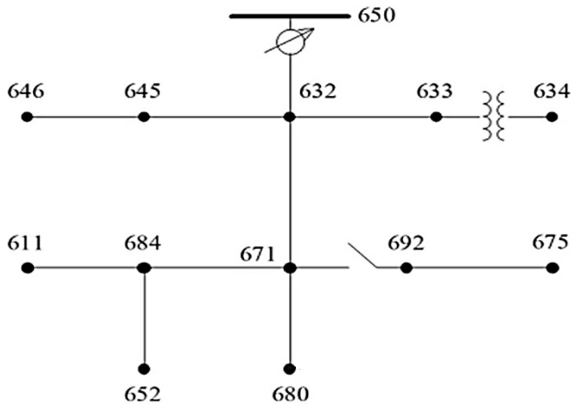

Fig. 2 IEEE 13 node test distribution network

c. IEEE 34 node test feeder: It is an actual distribution system located in Arizona, United States of America, with a substation voltage of 24.9kV. The IEEE 34 node test feeder is very long with light loading [9].

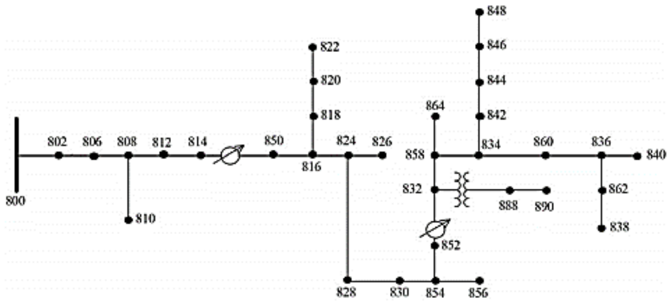

Fig. 3. IEEE 34 test feeders for distribution network

B. Load flow analysis

Load flow analysis aims to determine the present steady-state operating point of the power system; that is, the bus voltages, the current through the lines, the active and reactive power flow, and the active and reactive power losses. It is also very useful for the future expansion of the network under study. In load flow calculations, the nodes (or buses) of the network are categorized into three categories based on crucial quantities which are the active power (P), reactive power (Q), voltage magnitude (V), and phase angle (δ). These quantities permit the categorization of the nodes into three categories;

- Load bus (P-Q bus): Here, the active and reactive power are known, while the voltage magnitude and phase angle are unknown.
- Voltage controlled bus (P-V bus): Here, the active power and voltage magnitude of the bus are known, while the reactive power and the phase angle are unknown.
- Swing bus (slack bus): The slack bus injects or absorbs the required active and reactive power into or from the network

C. Formulation of Load flow equations

Power flow equations cannot be solved analytically because they are non-linear. Solving such problems calls for a numerical iterative technique. The procedure to formulate and solve power flow equations is as follows

a. Create a Y bus admittance matrix for the power network.
b. Calculate an initial estimate of the voltages (magnitude and phase angle) at each bus.
c. Incorporate the power flow equations, and then calculate any deviations from the answer.
d. Update the estimated voltages following several widely used numerical techniques such as Newton-Raphson or Gauss-Seidel.
e. Keep going through the process described above until there are a few deviations from the solution.

To illustrate the formulation of load flow equations, consider the following network with the transmission line represented in the normalized π model. R + jX is the impedance of the transmission line and $\frac{Y_{ij}}{2}$ is the half-line charging admittance.

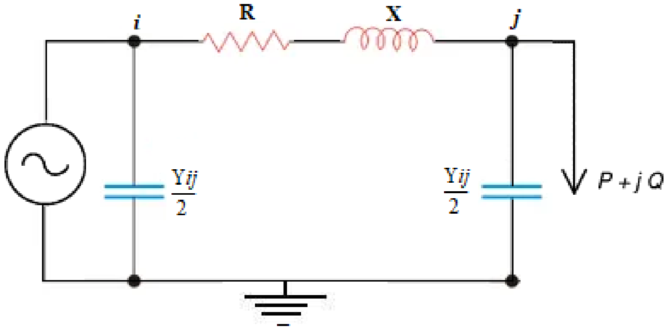

Fig. 4. Sample network for load equation formulation

From Fig. 4, the currents I_i, and I_j from nodes i, and j respectively can be expressed as

$$\begin{cases} I_i = V_i \dfrac{Y_{ij}}{2} + (V_i - V_j)(G_{ij} + B_{ij}) \\ I_j = V_j \dfrac{Y_{ij}}{2} + (V_j - V_i)(G_{ij} + B_{ij}) \end{cases} \quad (1)$$

Where V_i is the voltage magnitude at node i, V_j is the voltage magnitude at node j, $\frac{Y_{ij}}{2}$ is the half-line charging admittance, and $G_{ij} + B_{ij}$ is the reciprocal of the line impedance R + jX Equation (1) can be rewritten as;

$$\begin{cases} I_i = V_i\left(\frac{Y_{ij}}{2} + \left(G_{ij} + B_{ij}\right)\right) - V_j\left(G_{ij} + B_{ij}\right) \\ I_j = V_j\left(\frac{Y_{ij}}{2} + \left(G_{ij} + B_{ij}\right)\right) - V_i\left(G_{ij} + B_{ij}\right) \end{cases} \quad (2)$$

In Y matrix form, the line current is there expressed as

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} \dfrac{Y_{ij}}{a^2} & \dfrac{Y_{ij}}{a} \\ \dfrac{Y_{ij}}{a^2} & Y_{ij} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \quad (3)$$

The load flow equation can be written using the Y admittance matrix as

$$P_i + jQ_i = V_j \sum_j (V_j * Y_{ij})^* \quad (4)$$

D.Methods for solving power flow equations

There exist some methods for solving power flow equations, with the most common being, Gauss-Seidel, Fast Decoupled, and Newton-Raphson methods.

a. Gauss-Seidel (GS) method:

The Gauss-Seidal (GS) method is an iterative approach for resolving several algebraic non-linear equations. A solution vector is initially presumed based on advice from real-world experience in a physical setting. The present values of the other variables are then substituted into one of the equations to determine the revised value of a particular variable. Regarding this variable, the solution vector is immediately updated. One iteration is then completed by repeating the procedure for each variable. Until the solution vector converges within the required accuracy, the iterative process is repeated. The starting values that are assumed have a significant impact on the convergence. Fortunately, prior knowledge makes it simple to identify a beginning vector in a load flow analysis that is near to the ultimate answer. Some of the advantages of the GS method include

- The use of rectangular coordinates when programming
- It requires fewer arithmetic operations to finish an iteration due to the sparsity of the network matrix as well as the solution technique's simplicity.
- Easy to program

Some of the disadvantages of the GS method are

- Long computation time due to slow convergence
- Individual buses are treated standalone

b. Newton-Raphson (NR) method:

The NR method is an iterative technique employed to solve nonlinear equations with equal unknowns. NR uses two solutions methods; the first uses rectangular coordinates while the second uses polar coordinates for variables. The latter is mostly used compared to the former. Despite the heavy computational and storage requirements of the NR method, its convergence characteristics are still powerful. It requires a lesser number of iterations for convergence compared to GS if the initial guess is not distant from the expected final results. Some of the advantages of NR include;

- Has fewer iterations since its convegence characteristics are quadrature
- Faster and more accurate for larger systems compared to GS
- Unlike the Gauss-Seidel approach, which treats each bus independently and necessitates subsequent corrections to all the buses connected to it, the N-R method bases its voltage correction calculations taking into account all interactions.

Some disadvantages of NR are;

- Long computation time as all the elements of the Jacobian matrix needs to be computed at every iteration

c. Fast Decoupled Method:

The Newton-Raphson algorithm is approximated by the Fast Decoupled Power Flow Method (FDPFM) employing knowledge of the physical properties of electrical systems. The decoupling concept acknowledges the substantial correlation between active powers and voltage angles in the steady-state and between reactive powers and voltage magnitudes. This suggests that the two synthetic networks, P-δ and Q-V networks can be used to solve the load flow problem independently while making use of the real power-reactive power (P-Q) decoupling.

Despite the development of these various techniques, the most useful methods for load flow calculations in companies are the GS and the NR, with NR being used most.

E. Software packages

In this work, the efficiency of two software packages for unbalanced load flow analysis is examined critically. These are; ETAP and PASCAD.

a. ETAP:

The Electrical Transient and Analysis Program abbreviated as ETAP is a commercial comprehensive analysis platform for the design, operation, simulation, as well as automation of generation, transmission, distribution, transportation, and also industrial power systems [10]. It has an integrated digital twin platform. ETAP has an excellent human interface making it easily understandable. It is possible to do a variety of analyses in ETAP using the appropriate study modes such as balanced load flow, unbalanced load flow, motor starting analysis, ANSI short circuit analysis, harmonic analysis, star protection coordination, transient analysis, reliability analysis, optimum low flow, optimal capacitor placement, battery sizing analysis, DC short circuit analysis, and DC power flow.

b. PSCAD/EMTDC:

Power Systems Computer-Aided Design (PSCAD) is a flexible and powerful graphical user interface to the worldwide renowned EMTDC electromagnetic transient simulation engine [11]. PSCAD can be used for a range of applications such as power electronics, renewable (wind, solar, and distributed generations), protection and relays, equipment failure analysis, insulation coordination, research and development, and education [12].

F. Simulation

III. RESULTS AND DISCUSSION

The networks are initially built in ETAP and then exported to PSCAD using ETAP's data exchange (DataX) tool. In ETAP, it is possible to export an electrical diagram to PSCAD for analysis. The node voltages obtained after stimulation with both software packages are compared with published IEEE results as shown;

A. Case of IEEE 4 node test feeder

The voltage profile of the three phases of the network as obtained using ETAP and PSCAD compared to published benchmarked results are shown in Fig. 5, Fig. 6, and Fig. 7. It is seen that, the node voltages obtained with both software packages closely agree with benchmarked results with slight errors.

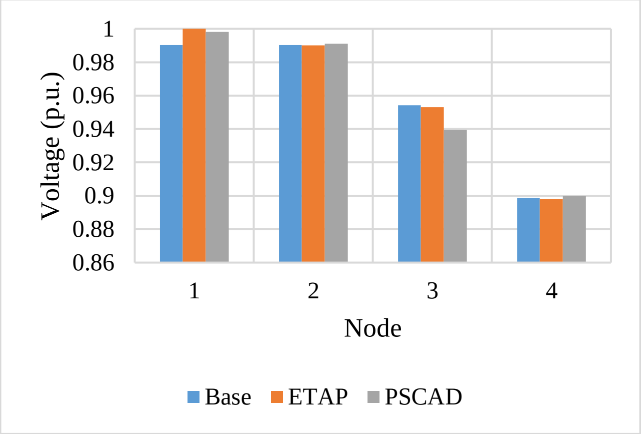

Fig. 5. IEEE 4 node test feeder's phase A voltage profile

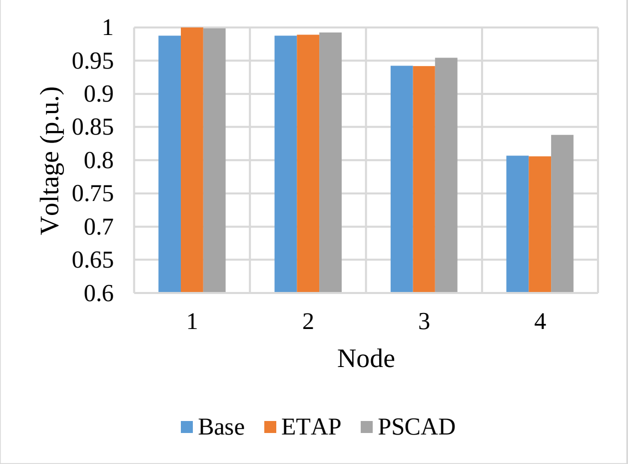

Fig. 6. IEEE 4 node test feeder's phase B voltage profile

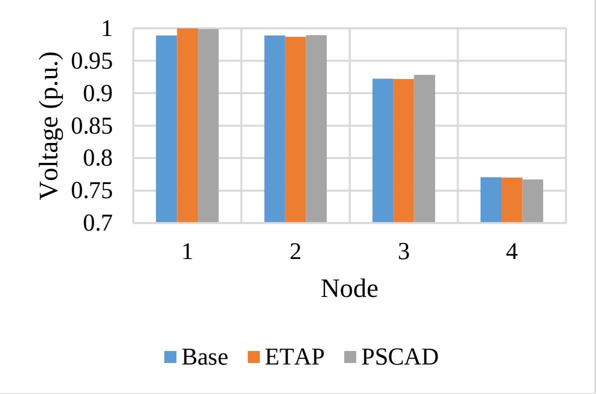

Fig. 7. IEEE 4 node test feeder's phase C voltage profile

The errors in the results obtained from both software packages are shown in Fig. 8, Fig. 9, and Fig. 10. Using ETAP, the smallest error in the node voltage is 0.0000833p.u., and it is seen in phase B of node 3 as shown in Fig. 9. Meanwhile, the largest voltage error, that is, 0.01251002p.u. is observed on phase B of node 1. On the other hand**,** using PSCAD, the smallest error in node voltage is seen on phase C of node 2, that is 0.00069p.u. as shown in Fig. 10. Meanwhile, the largest voltage error, that is, 0.014751p.u., is seen in phase A of node 3 as shown in Fig. 8. It is observed that the smallest voltage error using ETAP is smaller than that when using PSCAD, and the same can be said for the largest voltage error. It can therefore be deduced that ETAP yields better unbalanced load flow results than PSCAD in the load flow analysis of the IEEE 4 node test feeder.

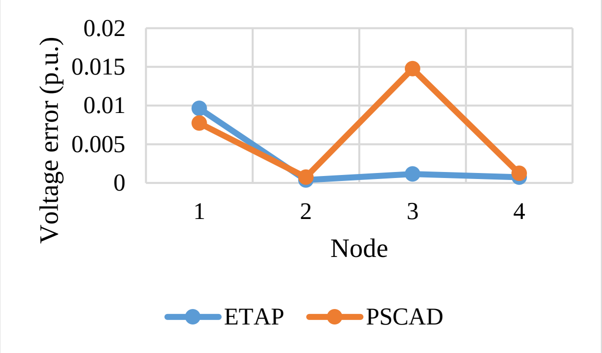

Fig. 8. IEEE 4 node test feeder's phase A voltage errors profile

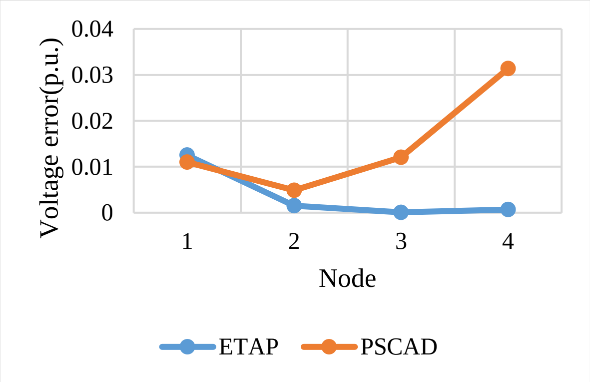

Fig. 9. IEEE 4 node test feeder's phase B voltage errors profile

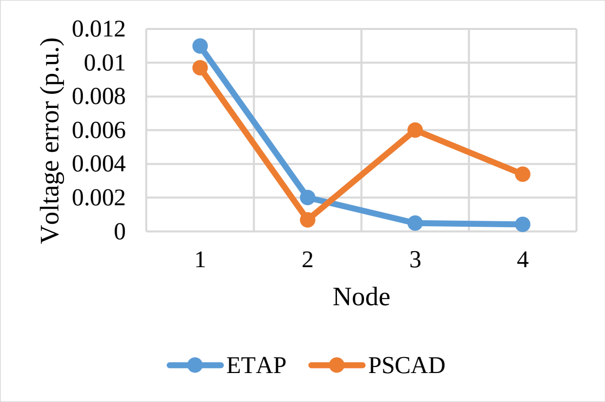

Fig. 10. IEEE 4 node test feeder's phase C voltage errors profile

B. Case of IEEE 13 node test feeder

For the case of the IEEE 13 node test feeder, the node voltages of the network as obtained using both software packages and compared to benchmarked results are shown in Fig. 11, Fig. 12, and Fig. 13. Just by looking at the node voltages of all the three phases of the network, it is seen that the results obtained using ETAP agree closer to published results compared to those obtained using PSCAD. The node voltages as obtained by PSCAD are farther from the benchmarked results.

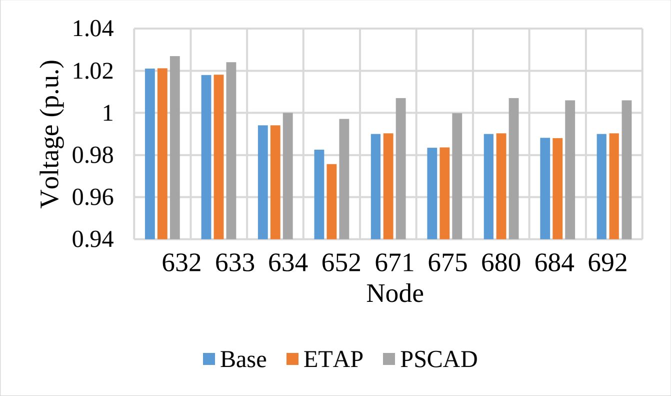

Fig. 11. IEEE 13 node test feeder's phase A voltage profile

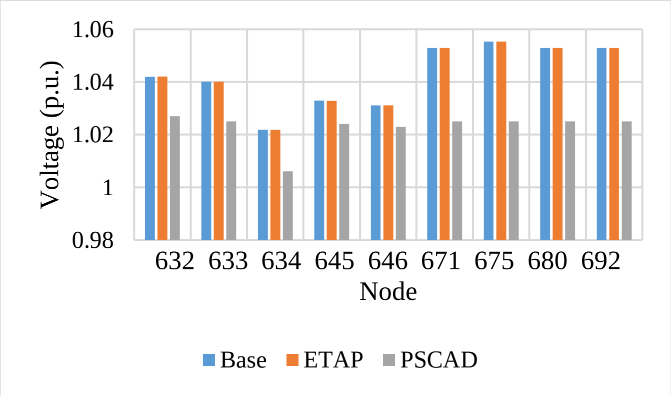

Fig. 12. IEEE 13 node test feeder's phase B voltage profile

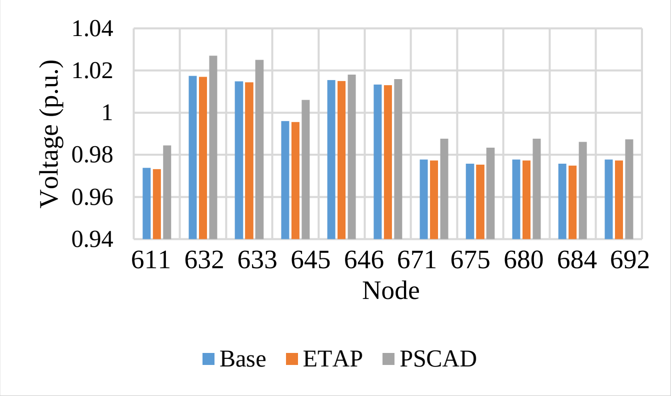

Fig. 13. IEEE 13 node test feeder's phase C voltage profile

The voltage measurement errors of the two software packages are shown in Fig. 14, Fig. 15, and Fig. 16. These figures clearly show how far the results obtained by both software packages are from the expected results. The drift in the node voltages in all the phases of the network as outputted by PSCAD can be seen, with the smallest voltage error being 0.0025p.u. as seen on phase C of node 646 as shown in Fig. 16, and the largest voltage error being 0.0303p.u. on phase B of node 675 as shown in Fig. 15. Meanwhile, the smallest voltage error in the results obtained by ETAP is 0.00p.u. as seen on phase B, of node 633, and 645, ash shown in Fig. 15, that is, the result obtained equals benchmarked results. While, the largest error in voltage is 0.006900p.u. observed on phase A of node 634 as shown in Fig. 14. It can, therefore, be said that, ETAP performs better in the load flow analysis of the IEEE 13 node test feeder compared to PSCAD.

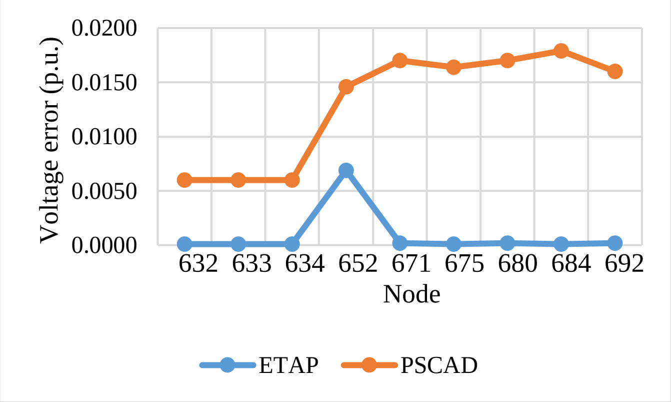

Fig. 14. IEEE 13 node test feeder's phase A voltage errors

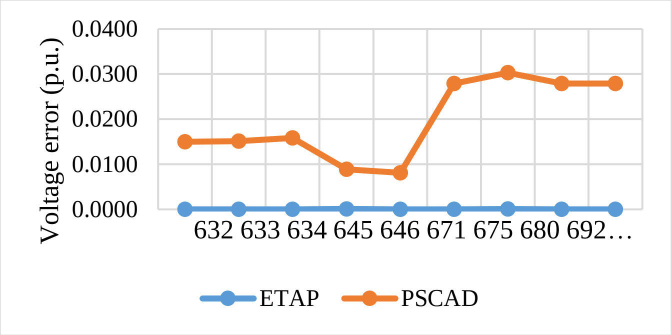

Fig. 15. IEEE 13 node test feeder's phase B voltage errors

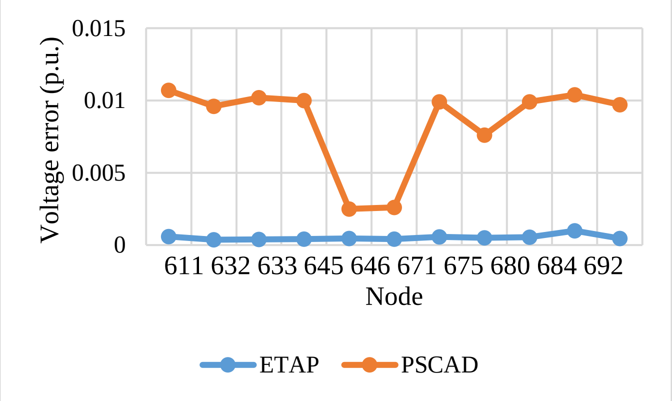

Fig. 16. IEEE 13 node test feeder's phase A voltage errors

C. Case of IEEE 34 node test feeder

For the case of the IEEE 34 node test feeder, the node votlages obtained by the software packages against benchmarked results are shown in Fig. 17, Fig. 18, and Fig. 19. It is observed that, for this test network, better node voltage results are obtained using PSCAD. Using ETAP, the largest voltage error is 0.0325p.u. in phase A of node 822 as shown in Fig 20. While the smallest voltage error is 0.003p.u. as seen in phase C of node 888. On the other hand, the node voltages as obtained using PSCAD closely agree with published results, with the smallest voltage error being 0.0001p.u. on phase A of node 848 as shown in Fig. 20, and phase B of node 828 as shown in Fig. 21, and the largest being 0.0059p.u. on phase B of node 890.

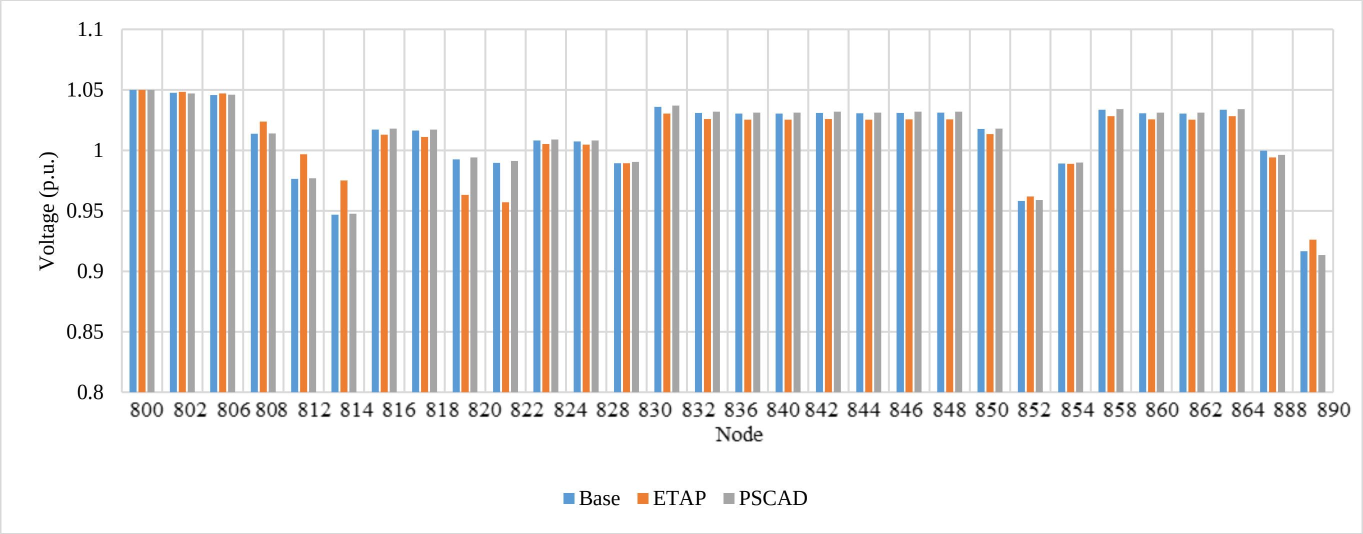

Fig. 17. IEEE 34 node test feeder's phase A voltage profile

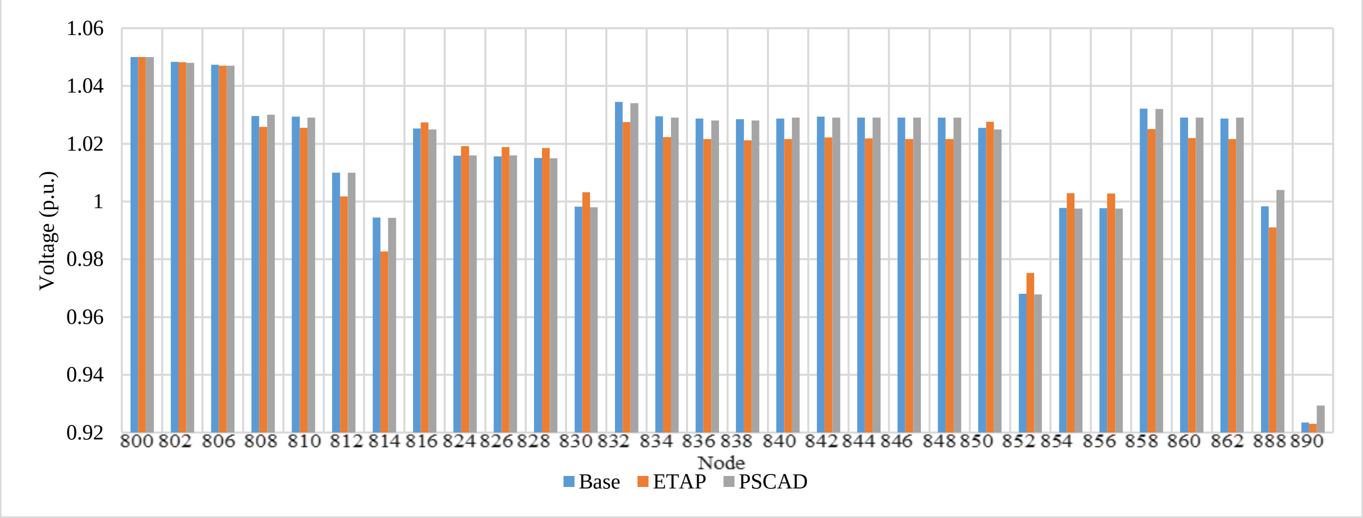

Fig. 18. IEEE 34 node test feeder's phase B voltage profile

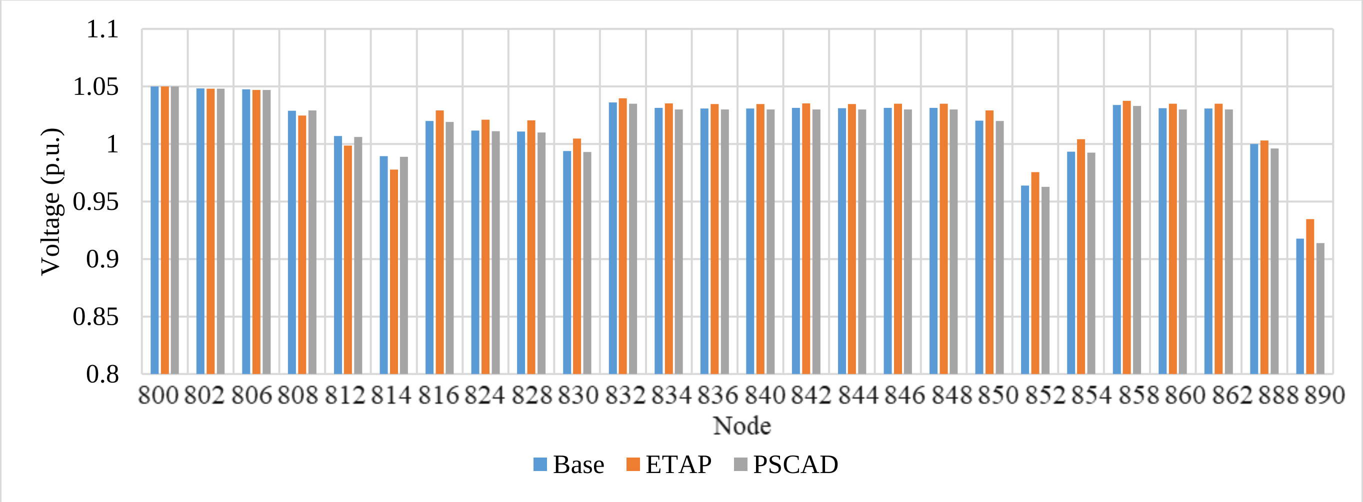

Fig. 19. IEEE 34 node test feeder's phase C voltage profile

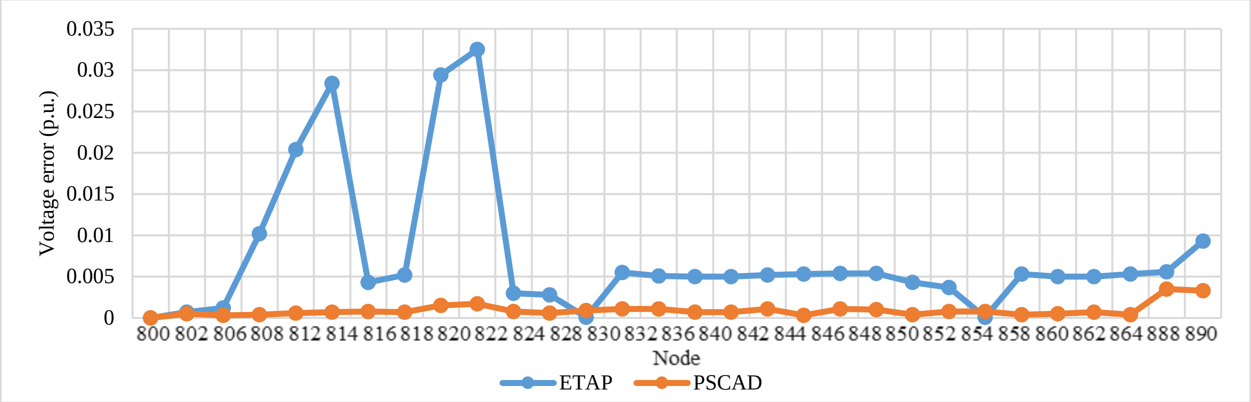

Fig. 20. IEEE 34 node test feeder's phase A voltage errors

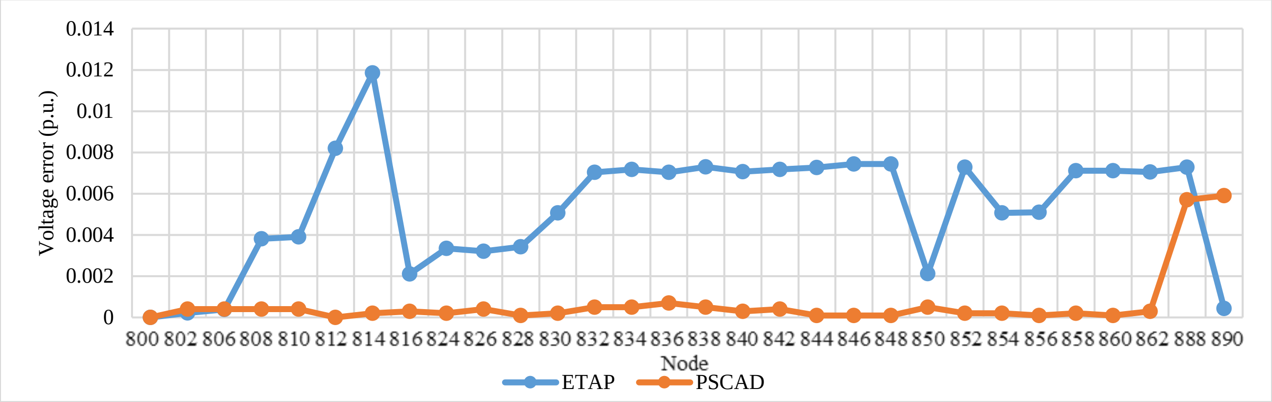

Fig. 21. IEEE 34 node test feeder's phase B voltage errors

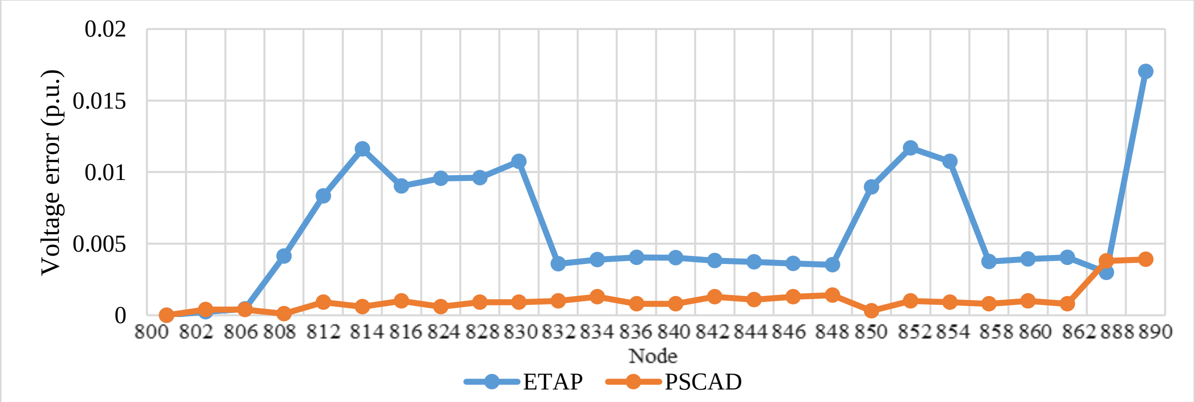

Fig. 22. IEEE 34 node test feeder's phase C voltage errors

IV. CONCLUSION

Load flow analysis is a crucial exercise in a power system as its target is to determine the current flow, bus voltages, and the real and reactive power flow in the network. Numerous software packages have been developed to ease this exercise and each of these software packages has its strengths and limitations. This paper focused on comparing the efficacy of ETAP and PSCAD for unbalanced load flow analysis. Three standard IEEE test feeders were used, that is, the IEEE 4 node, 13 node, and 34 node test feeders. Simulations results showed that for the case of the 4 node and the 13 node test networks, the node voltages obtained by ETAP agreed closer to benchmarked results compared to PSCAD. Meanwhile, for the case of the 34 node test feeder, the node voltages obtained using PSCAD agreed closer to published results compared to ETAP. In other to be able to conclude that one package is better than the other, it is necessary to consider test networks

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