05-003

LOAD FLOW ANALYSIS OF THE IEEE 34 NODE TEST FEEDER WITH INTEGRATION OF RENEWABLE ENERGIES

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Nowadays, the commitments made by governments worldwide on the reduction of greenhouse gas emissions, as well as the war situation that arose between Ukraine and Russia, which seriously affects Europe from the energy point of view, has motivated a great development of renewable energies. In order not to limit their expansion, grids must be prepared for the installation of these renewable energy sources and their impact on the electricity system in general. To analyze this impact, the "IEEE 34 Node Test Feeder" network is modelled and simulated in DIgSILENT PowerFactory®, because it is a network comparable to urban distribution networks where a massive implementation of generation system from renewable sources for self-consumption is taking place. Once the base grid has been modelled and simulated, renewable generation, wind and photovoltaic facilities are introduced along the network, with the aim of evaluating their technical-economic performance.

Keywords: IEEE; power system; load flow; wind; photovoltaic; DIgSILENT PowerFactory®

ANÁLISIS DE FLUJO DE CARGA DE LA RED IEEE 34 NUDOS CON INTEGRACIÓN DE ENERGÍAS RENOVABLES

En la actualidad, tanto los compromisos adquiridos por los gobiernos a nivel mundial sobre la disminución de las emisiones de gases de efecto invernadero, así como la situación bélica surgida entre Ucrania y Rusia, que afecta gravemente a Europa desde el punto de vista energético, ha producido un gran desarrollo de las energías renovables. Para no limitar su expansión, las redes de energía eléctrica deben estar preparadas para la instalación de estas fuentes de energía renovables y su impacto en el sistema eléctrico en general. Para analizar dicho impacto, se ha modelado y simulado la red "IEEE 34 Node Test Feeder" en DIgSILENT PowerFactory®, por ser una red equiparable a las redes de distribución urbanas donde se está produciendo una implantación masiva de sistema de generación a partir de fuentes renovables para autoconsumo. Una vez modelada y simulada la red base, se introducen instalaciones de generación renovable, eólica y fotovoltaica, a la largo de la red, con el objetivo de evaluar su comportamiento técnico-económico.

Palabras clave: IEEE; redes eléctricas; flujo de cargas; eólica; fotovoltaica; DIgSILENT PowerFactory®

1. Introduction

With the growing demand for electricity in recent years and the development of renewable energy systems, grids require tests and simulations to evaluate the integration capacity of new generation facilities from renewable sources into existing electricity networks.

These simulations help improve the systems created and develop improvements to meet current energy demands. Some of the most common networks are developed from model networks, which have been created to have a foundation on which to start designing systems and equipment. Such is the case of the Institute of Electrical and Electronics Engineers (IEEE), which provides users with model networks for implementation or study to obtain results applicable to future electrical network designs. In the literature, there are many studies that have used IEEE test feeders for their research: Scheneider et al. (2018) analyzed the different IEEE test feeders, Alvarez-Alvarado et al. (2022) used IEEE 39-node test feeder and DIgSILENT PowerFactory® to optimize the location and size of new solar and wind power plants by meeting frequency requirements in a distribution network, Alzahrani et al. (2020) verified the optimization of the location of battery energy storage systems in distribution networks with photovoltaics minimizing losses in the IEEE 37-node test feeder, Kaur et al. (2010) optimized generation economically to meet the operating requirements of the 30-node IEEE test feeder, Yadav et al. (2019) used DIgSILENT PowerFactory® in the IEEE 39-node test feeder in the transmission network of India for the classification of events in networks with integration of renewables, Montoya-Bueno et al. (2016) used the IEEE 34-node test feeder to test a new approach to manage uncertainty in distribution networks with integration of renewables minimizing distribution costs.

There is a variety of testing and simulation software on the market and its choice depends, to some extent, on the complexity of the calculations to be performed and their ease of use, for example, Kumar et al. (2015) compared tools such as NEPLAN®, PowerWorld®, PSAT® and MATPOWER®, for load flow analysis, Sultan et al. (2019) used DIgSILENT PowerFactory® to analyze PV penetration in Egypt by load flow analysis, Yan et al. (2011) used PSCAD® to study the influence of PV on the mains voltage, Zang et al. (2018) used Matlab® to develop a model a network with different load distributions and analyzed losses and voltage in the network before and after introducing solar PV.

The objective of this paper is to model and calculate the IEEE 34 node test feeder network in the DIgSILENT PowerFactory® electrical calculation software and compare it with the results obtained from the IEEE to obtain the minimum error.

Once the grid has been modeled, different generation scenarios from renewable energy sources will be simulated to evaluate how this grid would behave due to the addition of renewable energies.

2. Methodology

The generation, distribution and transmission of energy must be as efficient as possible at a minimum cost. Therefore, when energy is produced through different energy generation systems, the active and reactive energy generated must be maximum for minimum operating costs. Therefore, it is necessary to develop methods for the optimization of the performance of the available energy sources. These methods are based on complex mathematical algorithms that allow finding the exact operating point in the executed load flows to determine when the maximum point of efficiency at minimum cost occurs, obtaining all the data and parameters of the simulated network.

Basically, the load flow (also known as power flow) calculation involves the estimation of all the voltages (magnitude and angle) in a power system. Once the voltages are obtained, the computation of the active and reactive power flows in every equipment, such as lines and transformers, is straightforward. The methods commonly used for the load flow estimation are Gauss-Seidel and Newton Raphson, Acarnley (2012).

The Gauss-Seidel method is an iterative numerical procedure for solving load flows. Through the definition of a set of equations that contain the basic parameters of the network, a complex system of equations is created, which is solved through an iterative process until reaching a final solution that is within an acceptable error range. The Gauss-Seidel method is one of the simplest that exists for load flow analysis, however, in some cases, a high number of iterations is required to obtain a valid result, especially when the networks are large (i.e., a high number of nodes is found).

For this reason, the Newton-Raphson methodology, which improves and resolves some drawbacks of the Gauss-Seidel method, is the method commonly used by default by most of the software simulation platforms, such as DIgSILENT PowerFactory®. In fact, the Newton-Raphson method is currently widely used by most load flow calculation software available on the market. This method is characterized by its excellent convergence characteristics using quadratic convergence methods and is therefore superior to the Gauss-Seidel method in mathematical terms.

The Newton-Raphson method has the advantage that the number of iterations performed is completely independent of the size of the system. The study of load flows that this method develops is to transform the non-linear equations into linear ones. The non-linear equations that are used represent the active and reactive powers in terms of the bus voltage. Currently, DIgSILENT PowerFactory® implements this method in its internal mathematical development for its use and application in network simulation. In addition, it allows the user to modify the acceptable error ranges allowed, as well as the number of maximum iterations to be carried out.

The base equations used and that develop this method are:

$$P_i=V_i\sum_{j=1}^{n}V_j\ (G_{ij}\cos\delta_{ij}+B_{ij}\sin\delta_{ij}) \tag{1}$$

$$Q_i=V_i\sum_{j=1}^{n}V_j\ (G_{ij}\sin\delta_{ij}-B_{ij}\cos\delta_{ij}) \tag{2}$$

Where:

- P_i: active power injected into the node i.
- Q_i: reactive power injected into the node i.
- V_i: voltage magnitude in node i.
- G_{ij}, B_{ij}: Conductance (G) and susceptance (B) between node i and j.
- δ_{ij}: Difference between the voltage angles of node i and j. $\delta_{ij} = \delta_i$-δ_i

The error (or residual errors), that should be minimised, are calculated according to Eqs. (3) and (4), in which the $P_{i,set}$ and $Q_{i,set}$, represent the specified initial values:

$$\Delta P_i = P_{i,set} - V_i \sum_{j=1}^{n} V_j \ (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) \tag{3}$$

$$\Delta Q_i = Q_{i,set} - V_i \sum_{j=1}^{n} V_j \ (G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \tag{4}$$

For the estimation of the voltages (in magnitude and angle) at every node, the following Eq. (5) is used:

$$\begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} = -\ [J]^{-1} \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}, \text{where } J = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \tag{5}$$

The J matrix is the Jacobian matrix that applies first order partial derivatives to the vector functions of the different variables that comprise it, which is mainly based on the partial derivates of Eq. (1) and (2). This matrix will be defined by the parameters (H, N, M, L) being, in turn, expressed by the following equations:

Out of the main diagonal:

$$H_{ij} = L_{ij} = V_i V_j \left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right), \tag{6}$$

$$N_{ij} = -M_{ij} = V_i V_j (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}), \tag{7}$$

Inside of the main diagonal

$$H_{ii} = -Q_i - V_i^2 B_{ii}, \tag{8}$$

$$N_{ii} = V_i^2 G_{ii} + P_i \tag{9}$$

$$M_{ii} = P_i - V_i^2 G_{ii} \tag{10}$$

$$L_{ii} = Q_i - V_i^2 B_{ii} \tag{11}$$

Finally, once the corrections for the angle ($\Delta\delta$) and voltage magnitude have been obtained, they must be updated according to the following equations (k reflects the iteration number):

$$\delta^{K+1} = \delta^K + \Delta\delta^K, \tag{12}$$

$$V^{K+1} = V^K \left(1 + \frac{\Delta V}{V}\right)^K, \tag{13}$$

3. Case study

The case study includes two subsections, as follows:

- Modelling and validation of the IEEE 34 node test feeder in DIgSILENT PowerFactory®.
- Using this network as a basis for the simulation of its behaviour in power supply scenarios using renewable energy systems such as solar photovoltaic and wind power.

3.1. Data of study

The IEEE 34 node test feeder network is currently located in Arizona, with a nominal voltage of 24.9 kV. This network has a frequency of 60 Hz and is characterized by long line lengths between consumption points, two-line regulars, a section with a voltage reduction to 4.16 kV for private supply, capacitor banks at the furthest points and unbalanced loads that generate variability in the voltages and power at the connection busbars.

Firstly, the analysis and implementation of the network in the DIgSILENT PowerFactory® calculation software is performed. The characteristics of the equipment used must be defined, as well as the types of distribution lines, lengths and loads that make up the network. The data concerning the configuration of each node can be found in Su et al. (2014).

Secondly, the definition of the wind and incident radiation parameters, extracted from the database, and modelling energy production scenarios to test the behaviour of the modelled network over a given period and loads by means of quasi-dynamic analysis in DIgSILENT PowerFactory® is performed.

A renewable energy production system based on solar PV and wind power, with a nominal power of 20 kW was modelled at each grid node, according to Figure 1 and Figure 2, respectively.

Figure 1: Solar PV scenarios

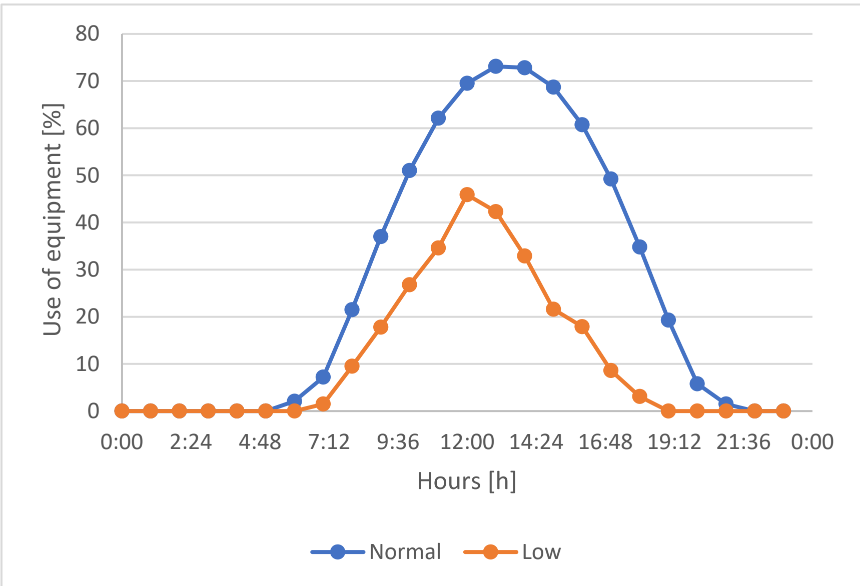
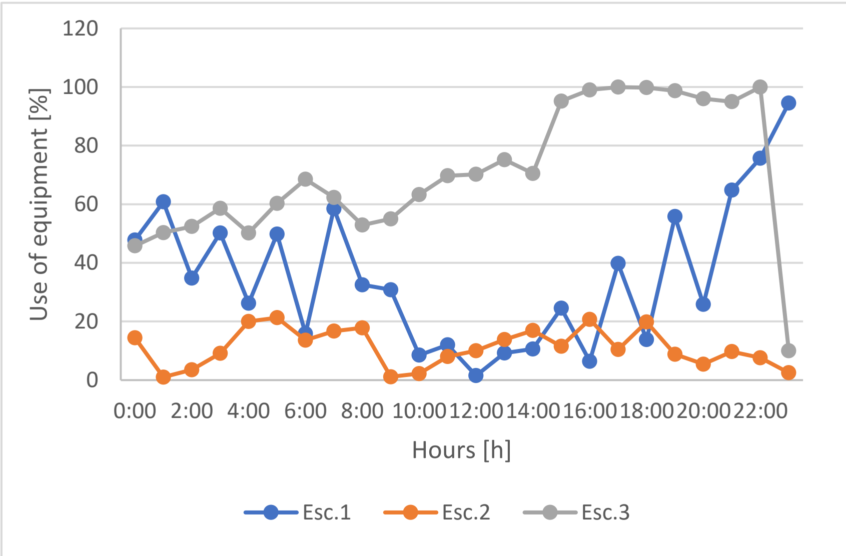


Figure 2: Wind scenarios



3.2. IEEE grid validation in DIgSILENT PowerFactory®

After entering all the parameters in the DIgSILENT PowerFactory® calculation software, results like those calculated by the IEEE organization were obtained. It was necessary to adjust the voltage regulator taps to match the designed model to the reference IEEE model. Therefore, the results obtained in terms of phase B bus voltages and power flows injected into the simulated network are shown in Figure 3 and Table 1 as an example.

Figure 3: Voltage validation (phase B)

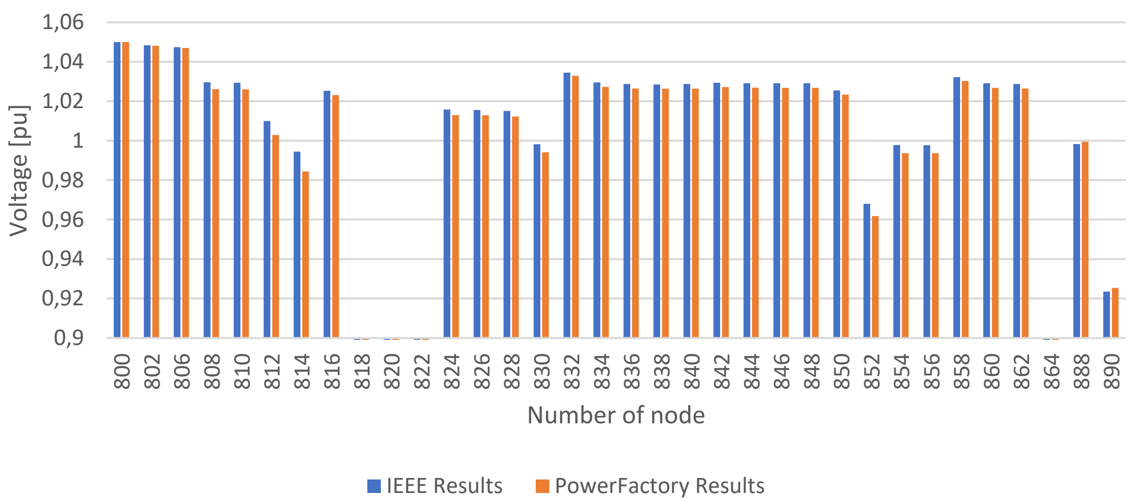
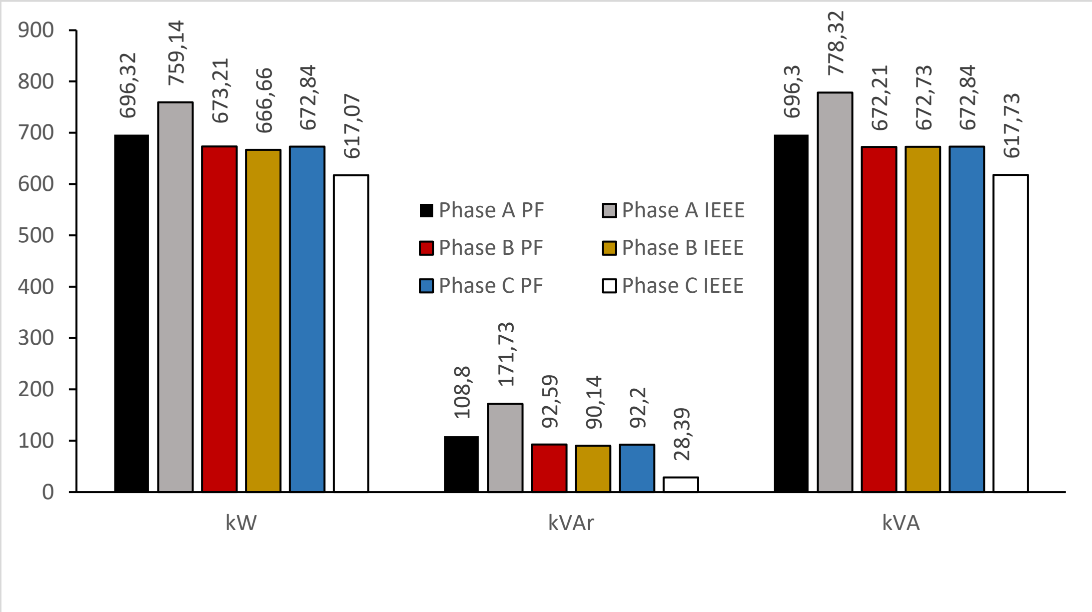


Table 1. Voltage validation (phase B)

	IEEE 34 Node Test	PowerFactory®	Error %
800	1,05	1,0500	0,0000
802	1,0484	1,0482	0,0217
806	1,0474	1,0470	0,0382
808	1,0296	1,0261	0,3402
810	1,0294	1,0261	0,3257
812	1,01	1,0029	0,7096
814	0,9945	0,9844	1,0224
816	1,0253	1,0231	0,2162
818	X	X	X
820	X	X	X
822	X	X	X
824	1,0158	1,0130	0,2772
826	1,0156	1,0129	0,2641
828	1,0151	1,0122	0,2816
830	0,9982	0,9941	0,4100
832	1,0345	1,0329	0,1593
834	1,0295	1,0272	0,2197
836	1,0287	1,0264	0,2199
838	1,0285	1,0264	0,2078
840	1,0287	1,0264	0,2234
842	1,0294	1,0272	0,2170
844	1,0291	1,0268	0,2219
846	1,0291	1,0268	0,2267
848	1,0291	1,0268	0,2243
850	1,0255	1,0234	0,2086
852	0,968	0,9618	0,6406
854	0,9978	0,9937	0,4155
856	0,9977	0,9936	0,4099
858	1,0322	1,0302	0,1897
860	1,0291	1,0268	0,2230
862	1,0287	1,0264	0,2218
864	X	X	X
888	0,9983	0,9994	0,1091
890	0,9235	0,9253	0,1998

Figure 4: Power validation



The sum of all phases to determine the incoming power flow is shown in Table 2:

Table 2. Power results

	kW	kVAr	KVA
PowerFactory® Results	2.042,37	292,79	2.063,25
IEEE Results	2.042,87	290,26	2.063,39
Error %	0,0244	0,8716	0,0067

According to Alvarado-Barrios et al. (2020), an error of less than 0.7% is considered valid, therefore the adjustment obtained with DIgSILENT PowerFactor® is validated.

Finally, it can be confirmed that the results of power flows show values similar to those obtained with the reference model. The network modeled in DIgSILENT PowerFactory® is shown in Figure 5.

4. Results of wind and solar PV cases in DIgSILENT PowerFactory®

The following results were obtained by analyzing the modeled grid node based on the implementation of solar photovoltaic and wind energy systems.

At table 3, it was observed that wind cases 1 and 2 had a favourable performance against constant energy demand. On the contrary, case 3 presented better voltage and power results than the other cases but compromised the reliability of the grid when an emergency shutdown situation occurred. This implied the need for external grid support and made it difficult to operate in island mode. At the time of peak energy demand, the grid had to provide power to make up for the low output of the wind generation systems.

Figure 5: IEEE-34 node test feeder

Table 3. Wind production

Wind Energy Production	Phase A (kW)	Phase B (kW)	Phase C (kW)	Total Power Injected from the external grid in maximum demand period
Case 1 (normal)	158,07	129,09	118,57	405,73
Case 2 (low)	408,61	375,29	364,40	1148,3
Case 3 (high)	88,53	62,67	52,24	203,44

As for solar PV, the normal production case was able to supply almost all the demand within its production period. However, due to the non-production of energy during night-time hours, it was essential to connect to an external grid to supply the demand within that period. The low production case had a similar behaviour to the previous one, with the difference that in the maximum performance points of the equipment, it was not possible to reach a performance higher than 28.62%, according to Table 4.

Table 4. Photovoltaic production

Single PV Energy Production	Phase A (kW)	Phase B (kW)	Phase C (kW)	Total Power Injected from the external grid in maximum production period (kW)	Total production energy (kW)	Equipment performance (%)
Case 1 (normal)	175,28	141,80	131,08	405,73	672,75	60,00
Case 2 (low)	334,19	296,32	286,56	917,07	367,78	28,62

5. Conclusions

The work developed in this article presents the modelling and analysis of the IEEE 34-node network and its behaviour through the integration of renewable energy systems.

From the results obtained by modelling the network in DIgSILENT PowerFactory® software, the following conclusions can be drawn:

- The initial values entered by running load flows show results far from those indicated by the IEEE. Therefore, manual adjustments to the voltage regulator taps were necessary to reduce the error made. It was observed that the manual adjustment of the taps caused a mismatch in the reactive power flows in the different phases. However, the simulated model achieved a more favorable balance of loads between the different phases.

Two (2) solar PV generation cases and three (3) wind generation scenarios were modelled. To test the behaviour of the renewable energy systems, a generation system was introduced at each grid node and the following results were obtained.

- Cases one (1) and two (2) of wind generation are the most suitable from a technical point of view, since they allow self-consumption and discharge of surplus energy to the grid during periods of low demand. The participation of the external grid is average in periods of high demand.
- Case three (3) presented good performance but the emergency shutdown situation compromised the reliability of the system. The external grid support is low in periods of high demand.
- The solar PV generation cases generate high variability in the system. During peak solar hours, case 1 has similar behaviour to case 1 for wind generation. However, during non-solar periods, external grid support is essential. Case 2 shows a scenario in which grid participation is constant for low production. It can be considered that in this situation, the installed systems help to reduce the consumption of external energy but do not allow to give more independence to the grid.
- To provide greater flexibility to the modelled network in the case of solar photovoltaic generation systems, the possibility of installing backup batteries for low production days or night-time periods was considered to reduce dependence on the external network. After the results obtained in both cases, the following conclusion was reached:
    - The solar production was not sufficient to obtain the highest performance from them.
    - The cost and maintenance nowadays increase the payback period.

As a conclusion, wind generation is a more favourable alternative to solar photovoltaic generation in the simulated environment, since at low wind speeds there is already energy production, while in the case of solar photovoltaic energy, night-time hours make it necessary to depend on an external grid to meet consumption needs.

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