Estudio de la Calidad de la Energía en Redes de Distribución con Alta Penetración de Energías Renovables usando Simulación en Tiempo Real

Power Quality Study in Distribution Networks with High Penetration of Renewable Energies using Real-Time Simulation

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Resumen

Introducción: La potencia que se suministra a la carga a través de la red de distribución proviene principalmente de fuentes convencionales de energía. Sin embargo, se está realizando una transformación hacia redes eléctricas sostenibles y eficientes, que incorporen fuentes de energía renovables distribuidas y más cerca a los consumos. Este proceso ha llevado a que se investiguen efectos que trae la inclusión de recursos energéticos distribuidos, los cuales han mostrado algunos problemas que se relacionan con la calidad de la energía. Sin embargo, se requieren más estudios para mostrar efectos más detallados y el uso de nuevas herramientas como la simulación en tiempo real.
Objetivo: Este documento utiliza simulación en tiempo real para evaluar el impacto en la calidad de la energía producida al integrar recursos de energía distribuida (DER) en una red de distribución.
Metodología: El sistema de alimentación de prueba de 13 nodos IEEE se utilizó para evaluar armónicos de voltaje, armónicos de corriente, parpadeo e inyección de CC según los estándares IEEE 1547-2018, IEEE 519-2014 y NTC 5001-2008. El sistema de prueba del alimentador se implementó en el software Hypersim y se utilizó para ejecutar simulaciones en tiempo real.
Resultados: Los resultados muestran que la integración de recursos energéticos distribuidos en la red produce un alto impacto en los armónicos de corriente de la red.
Conclusiones: El fenómeno de inyección DC presenta un impacto medio, y los flickers y armónicos de tensión presentan un impacto menor.

Palabras clave

Calidad de la energía; recursos energéticos distribuidos; simulación en tiempo real; armónicos; parpadeo; inyección de corriente directa.

Abstract

Introduction: The power supplied to the load through the distribution network comes mainly from conventional energy sources. However, a transformation is being made towards sustainable and efficient electricity networks, which incorporate distributed renewable energy sources and closer to consumption. This process has led to the investigation of the effects that the inclusion of distributed energy resources brings, which have shown power quality issues. However, more studies are required to show more detailed effects and the use of new tools such as real-time simulation.
Objective: This paper uses real-time simulation to evaluate the impact on the power quality produced by integrating distributed energy resources (DER) into a distribution network.
Method: The IEEE 13-node test feeder system was used to evaluate voltage harmonics, current harmonics, flicker, and DC injection based on the IEEE 1547-2018, IEEE 519-2014, and the NTC 5001-2008 standards. The feeder test system was implemented in the Hypersim software and used to run real-time simulations.
Results: The results show that integrating distributed energy resources into the network produces a high impact on the current harmonics of the network.
Conclusions: The DC injection phenomenon presents a medium impact, and flickers and voltage harmonics present a lower impact.

Key Words

Power quality; distributed energy resources; real-time simulation; harmonics; flicker; direct current injection.

I. INTRODUCTIÓN

In a typical power system, conventional energy sources are commonly used to supply power to loads. Hence, a transformation process is performed with renewable energy sources to obtain more sustainable, environmental, and efficient electrical networks [1], [2]. Thus, research has been conducted to evaluate the effects of the penetration of distributed energy resources (DER) into the system, showing affectations in the network [1], [3]–[5]. Some of these issues presented in the network are disturbances because of harmonics, blackouts, unbalanced voltage systems and voltage dips. [1]–[3].

In countries with high penetration of DER, such as the Netherlands, Germany, and Italy, undesirable blackouts and excessive regulation of harmonics in the network emerged [6]–[8]. Thus, DER incorporation requires an understanding of the events that occur in the electrical distribution network. In other words, a high level of distributed energy resource (DER) integration into the network results in poor power quality [9]. Harmonics evaluation when incorporating DERs into the network continues to be a matter of investigation [3]–[6], [10]–[12]. Therefore, incorporating DERs into the network requires measuring harmonics for power quality analysis and performing connection and feasibility studies.

This paper studies the impact on the quality of the electrical power of the distribution network produced by integrating DER into a distribution network using real-time simulation. HYPERSIM software is used to run simulations in a simple and fast way to process the voltage and current vectors. Furthermore, employing a code in MATLAB, the power quality indices of the network are calculated according to the definitions in IEEE Std 1547-2018 [13], IEEE Std 519-2014 [14], and NTC 5001-2008 [15]. Previous research has shown voltage distortions (THD_V) affecting the grid when including DER [1]. Therefore, this research demonstrates that depending on the type of network (strong or weak), when integrating distributed energy resources, it does not exceed the limits established by the standards presented in this paper. This is very important as it depends on whether the system operators make the decision to carry out said integration, based on what is regulated in its planning studies.

The rest of the paper has been organized into four more sections. Section 2 shows the mathematical formulation of power quality to evaluate the integration of DER in distribution networks. Section 3 presents the feeder test case used to implement the DER and evaluate the power quality. In section 4, the simulation scenarios and the results are described. Section 5 shows the results of the real-time simulation after evaluating the power quality of incorporating DER.

II. POWER QUALITY IN THE INTEGRATION OF DER

Power quality is the set of qualifiers of the voltage and current waveform, which evaluates the deviations from their standard shape and frequency [16], [17]. According to [18], integration of DERs into the electrical network can affect the voltage and current waveforms. Therefore, it is necessary to comply with the power quality parameters to guarantee that the operating conditions of the network are not affected by integrating DER [3]–[5].

The IEEE 1547-2018 standard establishes the criteria and requirements for the interconnection of DER to the distribution network [13]. In this standard, some recommendations are provided to measure the power quality of a network. The standard provides the technical conditioning of the DER implementation and the limitations of the phenomena, DC injection, flicker, and harmonics. A point of common connection (PCC) is used to measure the phenomenon that occurred in the distribution network, and each formulation is explained below.

A. Harmonics

Harmonics are caused when non-linear elements are connected to the network. Their impedance affects or changes the applied voltage, causing the current not to be proportionally related to the voltage, which generates a not sinusoidal voltage or current wave. The procedure defined in the IEEE 1547-2018 standard is used to measure harmonics [13]. Equation (1) shows the total harmonic distortion on the voltage signal (THD_V). The term h is the order of harmonics, V_h is the magnitude of the individual harmonics component (V_{RMS}) and V_1 is the magnitude of the fundamental component (V_{RMS}).

$$THD_V = \frac{\sqrt{\sum_{h>1}^{50} V_h^2}}{V_1} \times 100\% \tag{1}$$

The IEEE 519-2014 standard recommends using total demand distortion (TDD) to evaluate the current harmonic content. The TDD is calculated according to the expression given in Equation (2), and its measurement point is at the PCC. The term h is the order of harmonics, I_h is the magnitude of the individual harmonics component (A_{RMS}) and I_L is the maximum demand load current at the fundamental frequency component (A_{RMS}).

$$TDD = \frac{\sqrt{\sum_{h>1}^{50} I_h^2}}{I_L} \times 100\% \tag{2}$$

B. DC Injection

For the measurement of the DC current injection, the recommendations specified in the IEEE 1547-2018 are followed [13]. Here, the DC component (frequency less than 1 Hz) of the current in the PCC is measured. The DC component of the current is measured through the discrete Fourier transform, taking the 0 Hz component. Equation (3) shows the mathematical expression used to calculate the DC injection rate. Where I_o is the 0 Hz component and I_{rated} is the DER rated current capacity.

$$I_{DC} = \frac{I_0}{I_{rated}} \times 100\% \tag{3}$$

C. Flicker

The IEC-61000-4-15 standard presents the procedure to measure flickers [19]. Therefore, Equation (4) shows the mathematical expression to calculate flickers, presented in this case as P_{st}. The term P_i in this equation is represented by the flicker levels that exceed 0.1%, 1%, 3%, 10%, and 50% of the time during the observation period.

$$P_{st} = (0{,}0314P_{0.1} + 0{,}0525P_{1S} + 0{,}0657P_{3S} + 0{,}28P_{10S} + 0{,}08P_{50S})^{1/2} \tag{4}$$

All previous equations were implemented in MATLAB and calculated for multiple scenarios of the selected network.

D. Real-time simulation

Real-time simulation is an important tool for managing the complex operation of modern electrical systems. This tool compensates for the limitations of offline testing, while reproducing the complex operation of protection, control, and communications schemes. This solution offers benefits such as flexibility, quick commissioning, easy data depuration, and various tests. Different institutions have suggested modernizing and optimizing the electrical sector by including information and communication technologies in processes. The optimization of traditional testing and commissioning processes of electrical systems and equipment has been accomplished through powerful real-time simulators and new technologies [20].

Real-time simulation is used for closed loop testing of microgrids, DER and smart grids solutions. The simulator is useful to model a power system and works as an interface to test other devices. The simulator must provide real-time data to the equipment connected in the closed loop testing. With the power system simulation, different faults are easily evaluated under various network conditions to assess the performance of the protection, control, and communication systems. The trip signal will be sensed and the breaker in the simulation will be opened if a fault is detected by the protection. The real-time simulation allows testing interoperability among various IEDs [20].

The implementation was conducted in a simulation laboratory in real time. Figure 1 shows the scheme proposal. The technology OPAL 5600 reads the input signals during the real-time simulation, performs the calculations, and writes the output signals within the predetermined time step. Software in-the-loop (SIL) was used for real-time simulation, which provides a virtual simulation environment to develop and test large, complex systems such as microgrid. With Software in-the-loop, using a computer, systems can be tested and changed quickly, connecting the Hypersim software to the digital plant model and replacing expensive systems.

In an SIL scheme, both the controller and plant may be simulated in real time (Fig. 1) . This is very useful when it is difficult to access protection, control, and communications systems. However, all the devices must have the validated models to obtain accurate results [20].

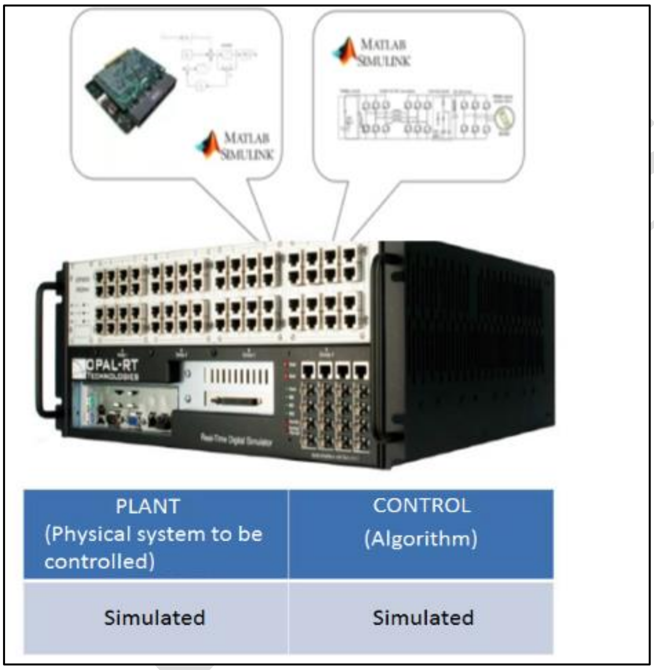


Fig. 1 SIL Scheme [20].

E. Case study network

A modified IEEE 13-node test feeder with renewable energy sources installed at different nodes was selected as the case study network. The network was published in 1991 by the IEEE PES, which has residential, commercial, and industrial loads. This network was chosen for its distribution voltage level of 4.16 kV and because this network has been used previously to validate this type of problem [21]. This is a small and heavily loaded radial distribution network with unbalanced loads, a voltage regulator at the main substation, and a capacitor bank. Figure 2 shows the case study network, which includes conventional generation and DER [10].

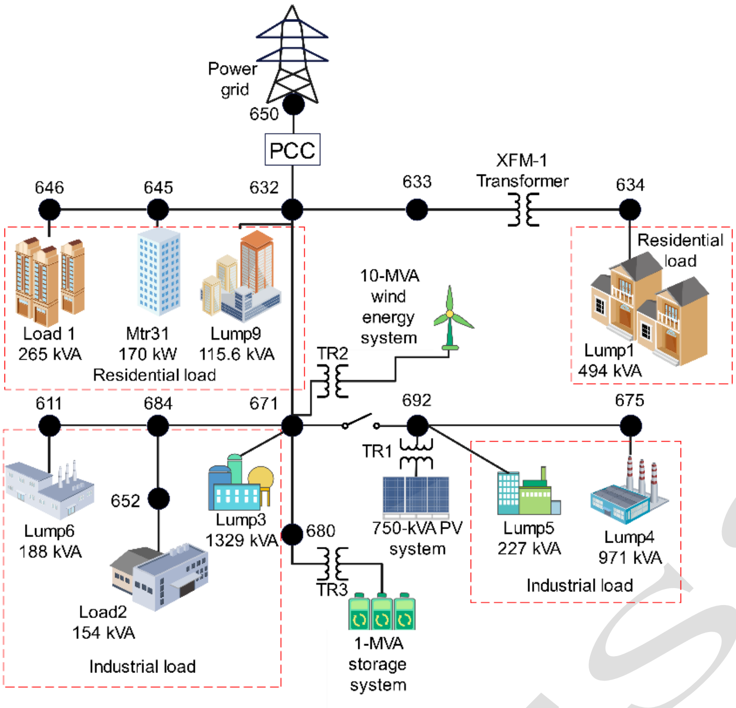


Fig. 2 IEEE 13-node test feeder used for the test.

This network has three types of generation sources in different nodes, such as wind, photovoltaic, storage system, and loads. The capacity of this wind power plant is 10MVA and varies depending on the wind speed (from 0 to 15 m/s). The solar plant has a capacity of 750KVA and varies according to the solar irradiation (from 0 W/m² to 1000 W/m²). The solar power plant contains an 12-pulses electronic converter with a phase-locked loop (PLL) controller of 60 Hz. The storage system comprises an Intensium® Max 20 lithium-ion smart battery bank (BESS), with a capacity of 1 MVA every 30 minutes. The system also considers a MaxSineTM eStorage smart converter. The IEEE 13 test feeder network is a highly loaded network that considers residential, commercial, and industrial loads.

F. Test scenarios

Power quality is evaluated using the IEEE 13-node test feeder through eight different simulation scenarios presented in Table 1. First, a zero scenario was defined as a baseline for the power quality study, which corresponds to the network without DER. Then, seven scenarios were defined to simulate critical conditions with the highest load consumption and different wind speed and solar irradiation profiles. These seven scenarios considered the input parameters for the simulation as solar irradiation, wind speed, load magnitude, and battery state of charge. They were created based on a typical day, with load profiles (residential, commercial, industrial), and the most common solar and wind generation profiles. These scenarios are defined to evaluate the impact on power quality when the DERs are delivering maximum power to the grid or when one of these sources is disconnected from the network.

Table 1 Scenarios for the simulation.

Scenario	Load (MW)	Solar irradiance W/m²	Solar irradiance kW	Wind speed m/s	Wind speed MW	SoC (%)	SoC kW
0	2.79	Excluded		Excluded		Excluded	
1	2.79	950	550	10	1.2	70	520
2	2.79	100	40	15	9.87	70	110
3	2.79	1000	560	15	8.87	70	98
4	2.79	1000	570	Excluded		70	455
5	2.79	Excluded		15	9.81	70	115

6	2.79	50	28	1	0	70	525
7	2.79	50	27	5	0.4	70	140

III. RESULTS AND ANALYSIS

Simulating an electrical network is complex because of the number of parameters and components to include in the model. In addition, renewable energy sources are incorporated, involving climatic variables, rotating machines, power electronics, and systems control, which represent a challenge compared to traditional offline simulation [10]. Real-time simulation is a solution that allows studying these complex systems and managing multiple scenarios and conditions to obtain a very close real behavior [10].

A. Validation of the network

Load flow and short circuit analyzes were first run without integrating DERs to validate the network. These results were compared with the data published by the IEEE PES [22]. Table 2 shows that the results obtained absolute errors very close to zero. Considering that different calculation methods are used for each software; then, the errors are acceptable to be used for the model in the real-time simulation.

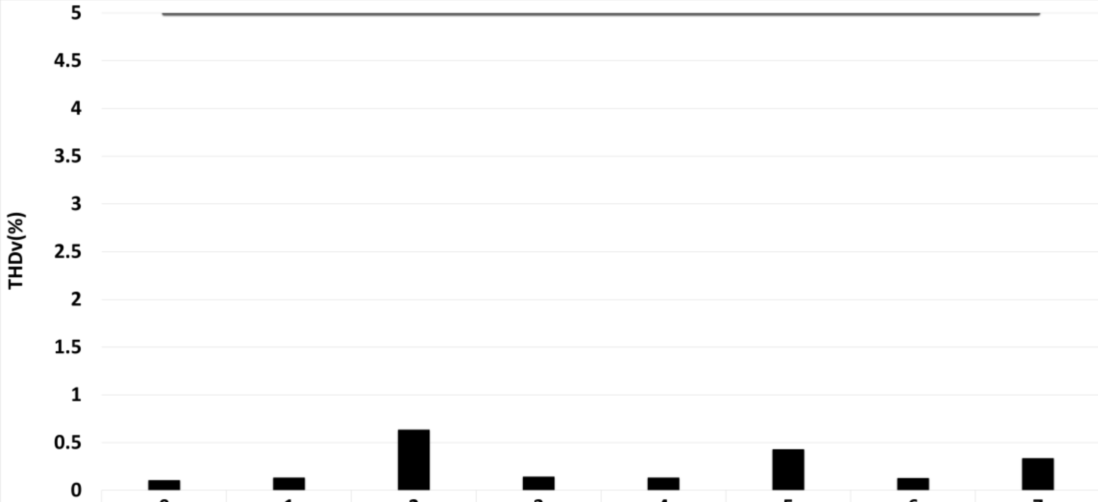
Table 2 Validation of the test network with the power flow.

ID Node	**HYPERSIM**				**IEEE PES**				**Absolute Error**			
	V	*Ang*	*P*	*Q*	*V*	*Ang*	*P*	*Q*	*V*	*Ang*	*P*	*Q*
Bus ID	[kV]	**[°]**	[MW]	[MVAr]	[kV]	**[°]**	[MW]	[MVAr]	[kV]	**[°]**	[MW]	[MVAr]
Bus611c*	4.16	-3.2	0.00	-0.1	4.17	-4.0	0.00	0.10	0.01	0.80	0.00	0.20
Bus611c*	4.16	-3.2	0.00	0.08	4.17	-4.0	0.17	0.08	0.01	0.80	0.17	0.00
Bus632	4.16	-2.1	0.10	0.06	4.27	-2.1	0.10	0.06	0.11	0.00	0.00	0.00
Bus634	0.48	-2.4	0.40	0.29	0.48	-2.6	0.40	0.29	0.00	0.20	0.00	0.00
Bus646b*	4.16	-2.1	0.16	0.00	4.22	-2.4	0.16	0.00	0.06	0.30	0.00	0.00
Bus646c*	4.16	-2.1	0.08	0.00	4.24	-2.0	0.08	0.14	0.08	0.10	0.00	0.14
Bus652a*	4.16	-2.5	0.12	0.00	4.12	-3.6	0.13	0.08	0.04	1.10	0.01	0.08
Bus671	4.16	-3.2	1.15	0.66	4.18	-3.8	1.15	0.66	0.02	0.60	0.00	0.00
Bus671	4.16	-3.2	0.10	0.06	4.18	-3.8	0.10	0.06	0.02	0.60	0.00	0.00
Bus675	4.16	-14	0.84	0.46	4.18	-3.9	0.00	0.60	0.02	10.10	0.84	0.14
Bus675	4.16	-14	0.00	-0.1	4.18	-3.9	0.84	0.46	0.02	10.10	0.84	0.56
Bus692	4.16	-3.2	0.20	0.15	4.18	-3.8	0.17	0.15	0.02	0.60	0.03	0.00

B. Power quality analysis

In the first place, the simulation of the network with the DERs disconnected was conducted to obtain a reference for the other scenarios. Next, the power quality indexes are evaluated after incorporating DERs with solar irradiance, wind speed, and the storage system. Then, each scenario is simulated to measure the harmonics, flicker, and DC current injection in the PCC.

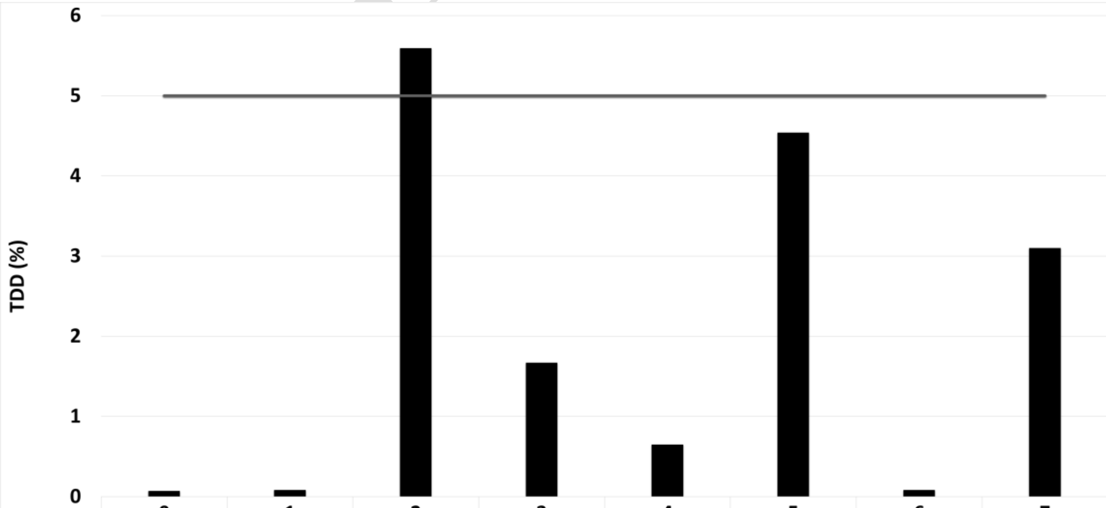
Figure 3 shows the behavior of voltage harmonic distortion in all scenarios. The line shows the limit established by the standards. In addition, each scenario is compared to the base test scenario (without DER). The THD_V measurement did not vary considerably, and although it did not remain constant in all the simulated scenarios, the limits required by the regulations were met. Therefore, the results presented in the present and previous studies show that the voltage does not suffer a harmonic affectation that exceeds the limits of the standards with the integration of DERs into the network.



	0	1	2	3	4	5	6	7
■THDv (%)	0.106	0.133	0.634	0.143	0.132	0.428	0.127	0.334
—Limit (%)	5	5	5	5	5	5	5	5

Fig. 3 Voltage harmonic distortion THD_V measurement results.

Figure 4 shows that the measurement of current harmonics through the TDD increases in such a way that they exceed the limits established by IEEE 1547-2018 [13], IEEE 519-2014 [14], and NTC 5001-2008 [15]. The current harmonics measured by the TDD index present a high impact when DER is incorporated into the network, as its value increases significantly. The line is the limit required by the standard, and each of the scenarios is compared with the base scenario siempre y cuando Isc/IL sea menor a 20 [14].



	0	1	2	3	4	5	6	7
■TDD (%)	0.071	0.084	5.594	1.67	0.65	4.54	0.082	3.1
—Limit (%)	5	5	5	5	5	5	5	5

Fig. 4 TDD measurement in the network.

Figure 5 presents the results of the DC injection in the network due to the integration of DER. The result shows that a medium impact in the values of DC injection is presented due to the incorporation of DER. However, the results always complied with the IEEE 1547-2018 [13], although there have been significant variations in the different scenarios. In addition, its value was always found close to the limit required by the standard, meaning that proper attention is required.

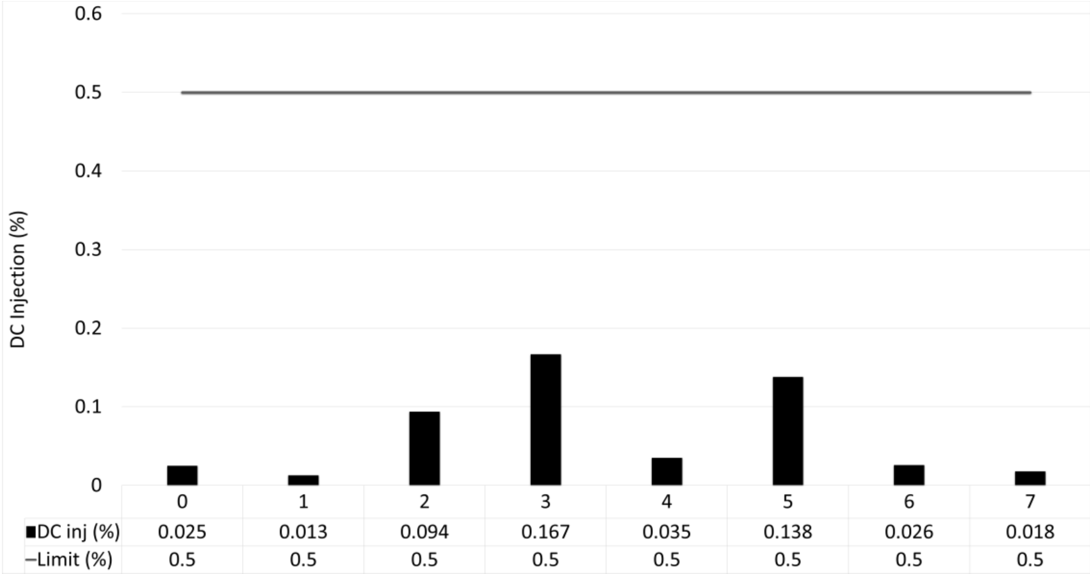


Fig. 5 Measurements of the DC injections.

Next, a summary of the results of the power quality analysis is presented in Table 3, including the limits required by the regulations. The network without non-conventional generation sources is identified as scenario 0. Once the DERs are incorporated according to the programmed scenarios, variations in the power quality indices are presented according to the changes related to the solar irradiance, wind speed, and the state of charge of the battery (SoC). The table shows the variation of the power quality indices, in which most of the power quality indices present variations, and they are marked according to complying with the limits established by the standards. However, during the simulation of scenario 2, the value of TDD exceeded the limits required by the standard.

Table 3 Results of the simulation scenarios.

Scenario	Load (MW)	Solar irradiance		Wind speed		SoC		THD_V (%)	TDD (%)	Flicker	DC injection (%)
		W/m²	kW	m/s	MW	(%)	kW				
0	2.79	Excluded		Excluded		Excluded		0.106	0.071	0.018	0.025
1	2.79	950	550	10	1.2	70	520	0.133✓	0.084✓	0.030✓	0.013✓
2	2.79	100	40	15	9.87	70	110	0.634✓	**5.594** ✗	0.033✓	0.094✓
3	2.79	1000	560	15	8.87	70	98	0.143✓	1.67✓	0.029✓	0.167✓
4	2.79	1000	570	Excluded		70	455	0.132✓	0.65✓	0.019✓	0.035✓
5	2.79	Excluded		15	9.81	70	115	0.428✓	4.54✓	0.031✓	0.138✓
6	2.79	50	28	1	0	70	525	0.127✓	0.082✓	0.016✓	0.026✓
7	2.79	50	27	5	0.4	70	140	0.334✓	3.10✓	0.029✓	0.018✓
Limits established by the standards								5%	5%	0.35	0.5%

In the reviewed literature, there are multiple studies of power quality directed towards renewable energies. This paper shows multiple similarities with these studies that support the behaviors found. According to the results obtained, current harmonics are some of the power quality issues faced by distribution networks when integrating renewable energy sources into the grid. Previous studies [1], [2], [11] and the IEEE 1547.2-2008 [13] support the above statement. Likewise, the TDD index increase with the level of penetration of renewable energy sources, as presented in this paper through the different scenarios simulated. The DC injection also shows a medium impact due to the incorporation of DER into the network. However, this phenomenon is not studied with the same frequency as current harmonics within the reviewed literature, except for regulations. Therefore, more attention should be given to this phenomenon in power quality studies [3].

Small harmonic variations could be presented because of the power conversion technology used by these unconventional alternating sources. Most of the negative effects on power quality, when DERs are incorporated, are caused by equipment that serves as the interface of the electrical system. In this study, there is a wind power plant with induction generators and the literature shows that this type of asynchronous machine has effects on the voltage and current harmonic distortion when the load varies, causing voltage sags, voltage swells, speed changes, or motorization. The system also had a battery bank and a photovoltaic system that requires power electronics such as inverters and rectifiers. Knowing that this network is a hypothetical test network for investigations, and according to [13], it can be affirmed that this is a not very robust network, which does not have an elaborate design for incorporating DER into the network. Therefore, it did not guarantee a good operation in the face of the interconnection with multiple generation sources.

The results show that the massive penetration of wind energy systems, photovoltaic panels, and storage systems produces power quality problems in the network. However, a power level or technical condition is not specified from which power quality problems appear. In the reviewed literature, no general optimal condition was found to know a point for incorporating DERs with a maximum limit, as it depends on the specific parameters of each system. Therefore, it is necessary to conduct a power quality study prior to interconnection to guarantee compliance with IEEE 519-2014 [14] and NTC 5001-2008 [15]. Hence, Table 4 shows a summary of the possible power quality issues that can occur in the distribution network with the integration of DERs [11].

Table 4 Possible power quality issues with the integration of DERs into the distribution network.

Phenomena	Impact	Possible affectation
Current harmonics	High	The temperature increases in transformers, which overheats the neutral conductors.
Voltage harmonics	Low	Overheating is presented in transformers which produces overheating in capacitor banks.
Flicker	High	Fluctuations in light loads can be natural to the client.
DC injection	Medium	Saturation of the transformer core causes the injection of current harmonics.

IV. CONCLUSIONS

In this paper, the impact on power quality caused by incorporating DER into a distribution network was studied. Real-time simulation and the HYPERSIM software tool were used to study under national and international quality standards, such as IEEE 519-2014, NTC 5001-2008, and IEEE 1547-2018. The voltage harmonics presented a low impact because of the incorporation of DER in the grid. The results showed that THD_V meets the limits required by the regulations after evaluating the different simulated scenarios. The current harmonics presented a high impact due to the incorporation of DER in the network. Furthermore, TDD showed significant variations because of different levels of penetration of renewable sources and the battery bank, exceeding the limits established in the regulations, so they must be considered for the installation. The DC injection requires special attention as it presented a medium impact when integrating DER, obtaining high values close to the limit required by the standard. As renewable energies are growing worldwide, the problem of current harmonics and DC injection will be much more severe. Therefore, massive penetrations of renewable energies produce great effects on the network, and it will be a great attention in the future of microgrids. Real-time simulations performed with the distribution network, including DERs, allowed saving time during the study compared to the time required to perform off-line simulations; this is because real-time simulation uses dedicated equipment to process different algorithms and obtains reliable results.

V. CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Eduardo Gómez-Luna: Conceptualización, Metodología, Investigación, Escritura – Revisión y edición, Supervisión. **Eduardo Marlés Sáenz:** Conceptualización, Metodología, Investigación Visualización, Supervisión. **John Edwin Candelo-Becerra:** Investigación, Visualización, Escritura – Borrador original, Escritura – Revisión y edición, Análisis formal.

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