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CASE REPORT

Assessment of the Incidence of the "Parque Solar Salinas" Photovoltaic Plant on the Medium Voltage Grid of the Emelnorte S.A. Company: A Comprehensive Report

Evaluación de la Incidencia del Parque Solar Salinas en la Planta Fotovoltaica sobre la Red de Media Tensión de la Empresa Emelnorte S.A.: Un Informe Exhaustivo

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ABSTRACT

This article presents a comprehensive analysis of the impact of the 'Parque Solar Salinas' photovoltaic (PV) plant on the medium voltage grid of Emelnorte S.A., a power distribution company located in the northern region of Ecuador. The main objective was to evaluate the power quality delivered by the plant, in compliance with the standards set by the Electricity Regulation and Control Agency of Ecuador (ARCONEL). The study was based on a detailed review of electrical generation, specifically focusing on solar PV energy. The components and topologies of PV plants, such as inverters, solar panels, and transformers, were described in depth. Additionally, the National Electrical Code regulations related to power quality were analyzed. The technical details of the plant is described, and the steps to determine the power quality are presented in the grid. Data were extracted from the plant, including variables such as active power, reactive power, voltage, and current. Short-term (Pst) and long-term (Plt) flicker were also analyzed and interpreted about solar radiation. The results obtained in this study were presented in a technical procedure manual that allowed for the evaluation of power quality for a photovoltaic plant when connected to a medium voltage grid.

Keywords: Power Distribution Company; Power Quality; PV Plant; Solar Radiation.

RESUMEN

Este artículo presenta un análisis exhaustivo del impacto de la planta fotovoltaica 'Parque Solar Salinas' en la red de media tensión de Emelnorte S.A., una empresa eléctrica ubicada en la región norte de Ecuador. El objetivo principal fue evaluar la calidad de la potencia entregada por la planta, en cumplimiento con las normas establecidas por la Agencia de Regulación y Control de Electricidad del Ecuador (ARCONEL). El estudio se basó en una revisión detallada de la generación eléctrica, con un enfoque específico en la energía solar fotovoltaica. Se describieron en profundidad los componentes y topologías de las plantas fotovoltaicas, como los inversores, paneles solares y transformadores. Además, se analizaron las regulaciones del Código Nacional Eléctrico relacionadas con la calidad de la potencia. Se describieron los detalles técnicos de la planta y se presentaron los pasos tomados para determinar la calidad de la potencia. Se extrajeron datos de la planta, incluyendo variables como la potencia activa, potencia reactiva, voltaje y corriente. También se analizaron e interpretaron el parpadeo a corto plazo (Pst) y el parpadeo a largo plazo (Plt) en relación con la radiación solar. Los resultados obtenidos en este estudio se presentaron en un manual de procedimientos técnicos que permite la evaluación de la calidad de la potencia de una planta fotovoltaica al estar conectada a una red de media tensión.

Palabras clave: Empresa Distribuidora de Electricidad; Calidad de Energía; Planta PV; Radiación Solar.

INTRODUCTION

Photovoltaic energy is an inexhaustible and clean source. In Ecuador, there has been a significant increase in renewable energy generation, especially solar energy, as the implementation of photovoltaic plants has required regulatory reforms and constant monitoring of the delivered energy quality. According to Jäger-Waldau et al.[1] and Escobar et al.[7], the variability of solar radiation affects energy quality, especially active and reactive power, highlighting the importance of evaluating and controlling these aspects for optimal operation and economic loss reduction.

Energy quality standards establish parameters such as frequency, voltage level and fluctuations, harmonics, voltage and current imbalance, power factor, sags, and overvoltage. As mentioned by Becirovic et al.[2], complying with these standards is essential to ensure the reliable distribution of generated solar energy where the electronic inverter appears.

The inverter is an essential component in photovoltaic plants. It converts direct current (DC) solar energy into alternating current (AC), allowing integration with the conventional electrical grid with transformers[11] be used in electrical and electronic equipment.[3,4] Solar panels are semiconductor devices that directly convert sunlight into electrical energy through the photovoltaic effect. They are composed of photovoltaic cells that release electrons when impacted by sunlight, generating a continuous electrical current (DC).[3] This current can be used directly or converted into alternating current (AC) through an inverter for integration into the electrical grid or use in conventional systems.

A transformer is an essential electromagnetic device used to convert and adjust the voltage of electrical energy generated by solar panels. According to Krishnan et al.[5] and Vilca Choque et al.[6], its main function is to facilitate efficient transmission of energy from the photovoltaic plant to the distribution or consumption grid, allowing the generated electricity to adapt to the required levels for use in conventional electrical systems.

According to Helać et al.[8], energy quality refers to the evaluation and assurance of stability and reliability of the energy generated by solar panels. It focuses on ensuring that the produced electricity complies with predetermined standards for distribution and use in the conventional electrical grid. This involves monitoring and analyzing parameters such as voltage, frequency, fluctuations, and distortions to ensure a stable and secure power supply.

A medium-voltage network is an electrical distribution system that carries the energy generated from production centers to consumption points.[9] Its function is to handle higher electricity loads and uses transformers to adjust voltage levels. Efficient design and operation are essential for stable and safe energy distribution.

Harmonics are additional currents or voltages generated due to waveform distortion, while disturbances are undesirable variations in the waveform caused by sudden changes in load or external interference.[10]

In conclusion, the technical procedures manual facilitates important decision-making regarding the optimization of the energy system.[12] Controlling factors that influence energy quality is essential for optimal operation and economic loss reduction. Ultimately, photovoltaic energy is positioning itself as an ecological and sustainable solution to meet current energy demands.[13,14]

Parameters of analysis in PV generation and power quality studies

Emphasis is placed on the function performed by each element within the systems, the variables for monitoring, and the parameters for control.

Photovoltaic Panels

Photovoltaic panels are essential semiconductor devices in the generation of electrical energy from sunlight through the photovoltaic effect. They directly convert solar radiation into direct current (DC) electricity.

Power Inverter (SFCR)

A Photovoltaic Inverter (SFCR) is an essential component in photovoltaic generation systems, its main function is to adapt the energy generated by the solar panels to the standards of the conventional electrical grid in terms of frequency, voltage, and power quality. SFCRs must comply with specific power quality regulations and are equipped with maximum power point tracking (MPPT) mechanisms to maximize the conversion process. Precise control of the SFCR ensures a safe and reliable integration of solar energy into the electrical grid.[6]

Transformer

The transformer in photovoltaic generation systems uses electromagnetic induction to convert the voltage of the solar energy generated by solar panels to appropriate levels for distribution in the electrical grid or for use in conventional systems.[5]

Photovoltaic plant Topologies

According to Cipriani et al.[12], PV plant topologies refer to the different configurations and designs used for the connection and arrangement of solar panels and inverters. There are centralized topologies, where all panels are connected to a single inverter; and distributed topologies, where multiple inverters are used throughout the plant. There are also hybrid topologies that combine characteristics of both. The choice of the appropriate topology depends on factors such as the size of the plant and solar irradiation.

Disturbances in the Electrical Grid

Disturbances in the electrical grid are undesirable variations in the current and voltage waveform. In PV plants, these irregularities can negatively affect the quality of the generated energy and damage connected equipment.[13] Common problems include harmonics, flicker, voltage sags, and overvoltages. Implementing appropriate control and protection measures is required to mitigate the effects and ensure optimal and reliable operation of the photovoltaic plant. Real-time monitoring is essential for detecting and correcting any anomalies.

Power Quality and its Regulation

Power quality refers to the compliance of electrical parameters with established standards for distribution and use in the electrical grid. In PV plants, it is vital to ensure that the generated energy meets predefined requirements to avoid disturbances and ensure a stable and reliable electrical supply.

Analysis and Evaluation of the "Salinas Solar Park" Photovoltaic Plant

The "Salinas Solar Park" photovoltaic plant is located in Urcuqui, Imbabura, Ecuador at 5 km from the (Salinas-Urcuquí) road, at an altitude of 1800 meters above sea level, with an average radiation of 5,1 kWh/m^2/day.

Figure 1 shows the main components of the PV generation in the "Salinas Solar Park" Plant. The project was developed by Gransolar S.A. and is divided into the "Salinas Train" (999 kW, 2,27 ha) and "Salinas" (2 MW, 3,98 ha) sections, reaching a total generation of approximately 3 MW. The energy is transmitted 35 km to feeder number 4 of the Alpachaca substation, owned by Emelnorte S.A. Considering the stages presented in figure 1., the photovoltaic plant consists of multiple photovoltaic generators. In this case, it has 6 generators, each with their corresponding solar panels and central topology inverters.

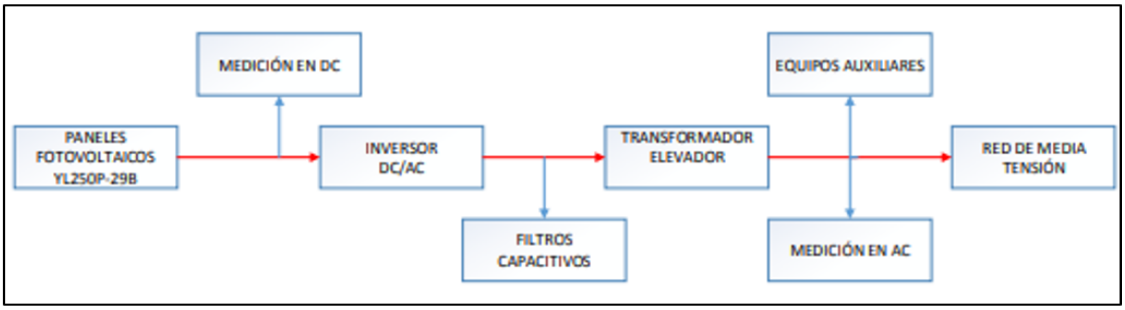

Figure 1. Main Components of a PV plant "Parque Solar Salinas"

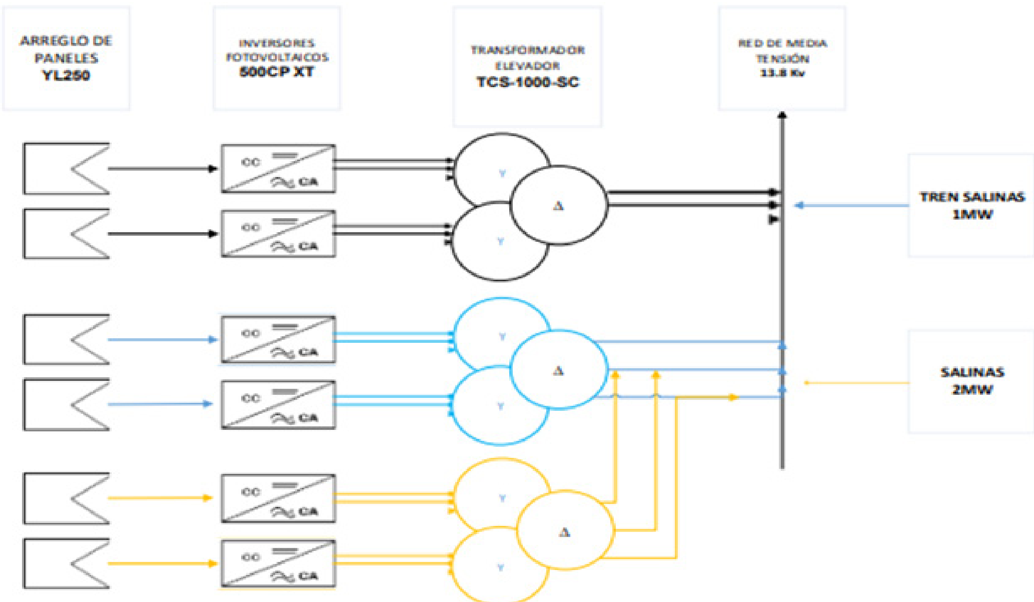

Figure 2. Diagram of the "Salinas Solar Park"

Each group of 2 inverters is connected to the medium voltage grid through a triple-wound transformer. The overall diagram of the photovoltaic plant can be seen in figure 2.

Yingli Solar panels

Yingli Solar photovoltaic panels have been used in the project. In total, the installation has 14 800 modules, of which 4800 are in the Salinas Train section and 9600 in Salinas. These panels, identified as YL250P-29P, have a power output of 250W and have been evaluated considering a radiation of 100W/m^2 and an ambient temperature of 25°C.

Figure 3. String combiner panel

The interconnection of the photovoltaic modules with the inverter in the PV is done through a string combiner box, which is presented in figure 3. Specifically, a connection box from the SOLARMAT brand has been used, which allows for the series connection of up to 20 solar panels. Additionally, this connection box has a continuous monitoring system to constantly supervise the performance of the modules. Table 1 and table 2 shows a more detailed group o characteristics of the PV plant.

Table 1. Characteristics of each solar panel YL250P-29P

Power	250	W
Eficiency	15,3	%
Voltage to Pmax	30,4	V
Current to Pmax	8,24	A
No load voltaje	38,7	V
Short circuito current	8,98	A

Table 2. Characteristics of string combiner panel

Maximum DC input voltaje	1 000 VCC
Fuse	16A
External DC supply voltage	35 VCC -55 VCC
Maximum section of the cable	300 mm2
Suitable connection material	Copper/aluminum
Number of String fuses per potential SSM8-21-BS/SSMB-21-BS-JP	16
DC current switch-disconnector	280 ADC

Sunny central 500cp XT inverter

In the "Salinas Solar Park", the electrical energy produced in direct current (DC) by the PV modules is converted into alternating current (AC) using a SUNNY CENTRAL 500CP XT inverter (figure 6), which has an efficiency of 98 %. It has a maximum power of 560 kW (DC) and it can deliver a maximum power of 550 kW (AC). Its function is crucial for reliably integrating the generated solar energy into the conventional electrical grid, table 3.

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Table 3. Technical data of the Sunny Central 500CP XT inverter	
DC INPUT DATA	
Maximum DC power	560 kW
Maximum DC voltage	1000 V
Minimum voltage to start power	400 V
AC OUTPUT DATA	
AC Maximum power	550 kW
AC Maximum voltage	500 kV
AC output voltaje range	243-310V
Rated operation voltage	270V
AC maximum current	1,176A
Power factor	1
Number of phases	3
Eficiency	98,6 %
GENERAL DATA	
Weight	1900 kg
Nocturnal consumption	< 100 W
Protective class	IP43, IP54
Operating temperature	25 + 62°C range
Interface	RS 485 Ethernet

TCS-1000-SC transformer

After the process of converting direct current (DC) energy into alternating current (AC), the latter is directed towards the compact three-phase transformer TCS-1000-SC. With a capacity of 1000 kVA, the transformer is composed of three windings: two on low voltage with "Y" connection and one on medium voltage with "DELTA" connection.

The configuration of the transformer, identified as (Dy11y11), represents the delta (triangle) connection on the high voltage side and the star (Y) connection on the low voltage sides, as shown graphically in figure 4. It is relevant to highlight that the transformer plays a crucial role in stepping up the voltage generated by the inverter to make it compatible with Emelnorte S.A.'s medium voltage grid. Table 4 provides detailed technical information on the specifications and characteristics of the TCS-1000-SC transformer.

Table 4. Technical data of the Transformer TCS-1000-SC	
Medium Voltage Side	
AC rated power	1000 kVA
Working voltage, mains ±10 %	20 kV
Low Voltage Side	
Input voltage	270 V
General data	
Protection type	IP23
Permissible ambient temperature	-20°C a +45°C
Maximum altitude above sea level	1000 m
Self supply transformer	6kVA

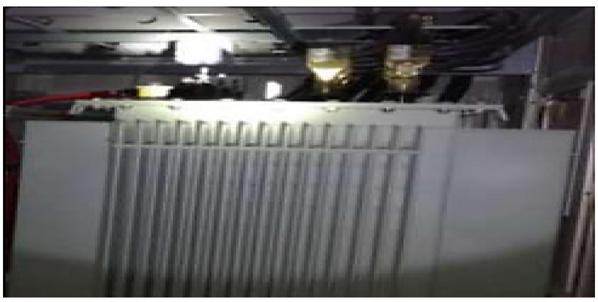

Figure 4. Transformer TCS-1000-SC

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Power quality in a PV plant

A comprehensive analysis of the "Salinas Solar Park" photovoltaic plant was carried out, considering the current national standards established by ARCONEL, the energy regulatory body in Ecuador. To conduct the power quality evaluation, a specific procedure is followed. Firstly, a detailed visual inspection of the installations is performed to identify the necessary measurement points. This is crucial to ensure that the appropriate and representative information is collected from the plant. Once the measurement points are identified, an information gathering process is carried out, which involves installing analyzers at the outputs of each inverter and transformer, as shown in figure 5.

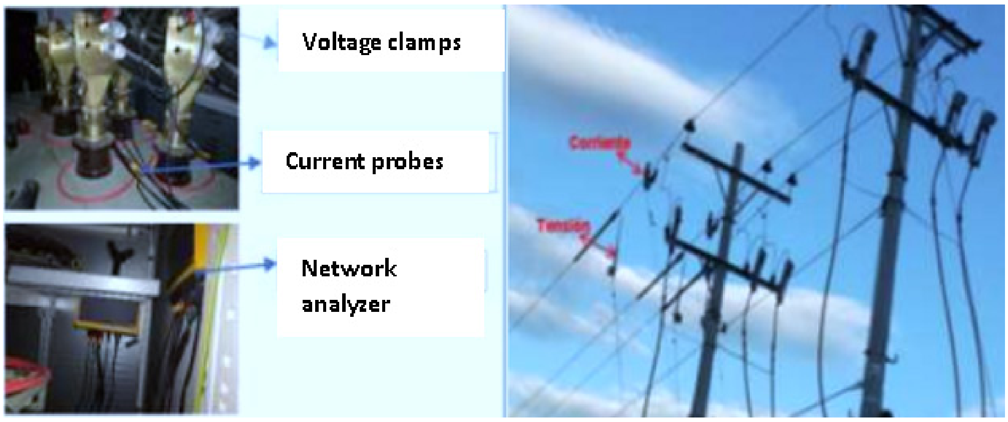

Figure 5. Network analyzer connection

The installation of the network analyzers was carried out in close collaboration with Emelnorte S.A., the local power company. This process extended from June 12th to June 18th, 2018, as can be seen in figure 5, to ensure a comprehensive and representative data collection. In the next stage, each analyzer was programmed to acquire data every 10 minutes over a period of 7 days. This sampling frequency allowed for a detailed insight into fluctuations and trends in key electrical variables, as well as power quality indicators Pst, Plt, and THD.

Pst (Short-Term Flicker Perceptibility)

Measures rapid voltage variation in short periods of time.

Plt (Long-Term Flicker Perceptibility)

Measures longer-term variations in voltage and represents the subjective perception of fluctuations over time.

THD (Total Harmonic Distortion)

Measures the sum of all harmonic distortion in the voltage or current.

Analysis of Data Extracted from the "Salinas Solar Park" PV Plant

The results of the analysis of the operating parameters are described. Thus, a comprehensive analysis was carried out on the variables covered by ARCONEL Regulation 004/15, particularly those related to active power, reactive power, power factor, voltage, Pst, Plt, and THD of voltage, and their correlation with solar radiation of figure 6. Focus was placed on June 12th, 2018, and the subsequent 6 days. Furthermore, results were compared with the limits in regulation.

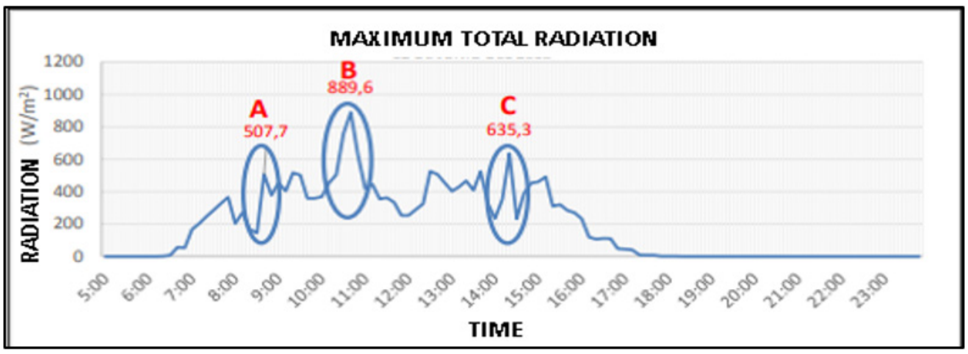

Figure 6. Maximum total radiation

Relation of active power and solar radiation

The analysis of active power reveals three zones of interest in figure 7. In zone A, the power rapidly changed from 136,501 kW to 478,118 kW in less than 10 minutes, with a ramp rate of 34,16 kW/min. Zone B exhibits a notable variation, reaching 837,724 kW from 347,424 kW in less than 20 minutes, with a ramp rate of 34,7 kW/min. In zone C, there is a change from 219,908 kW to 598,260 kW in less than 20 minutes, with a ramp rate of 18,91 kW/min. Additionally, during this time, solar radiation decreased from 642 W/m2 to 235 W/m2 in 20 minutes, with a ramp rate of 20,3 kW/min.

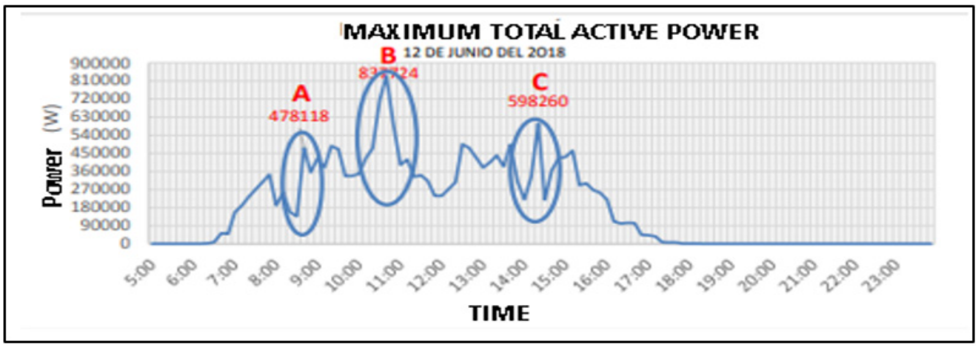

Figure 7. Active power vs. Solar radiation

Relation of reactive power and solar radiation

The analysis of reactive power revealed three zones of interest in figure 8. In zone A, reactive power varied rapidly from 30,502 kVAR to 147,494 kVAR in less than 20 minutes, with a ramp rate of 5,84 kW/min. In zone B, values reached 160,831 kVAR, ranging from 29,217 kVAR to 160,831 kVAR in less than 30 minutes, with a ramp rate of 6,58 kW/min. In zone C, there was a more pronounced change from 23,059 kVAR to 177,447 kVAR in less than 10 minutes, with a significant ramp rate of 15,43 kW/min. Additionally, in zone C, solar radiation decreased from 534 W/m² to 235 W/m² in 20 minutes, with a ramp rate of 14,91 kW/min.

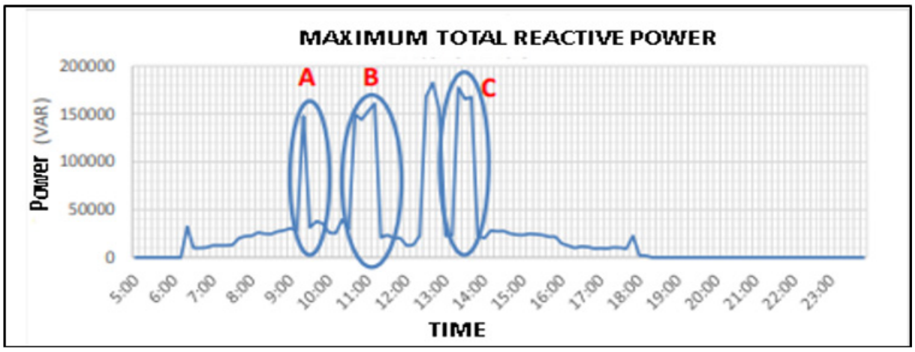

Figure 8. Reactive power vs. Solar radiation

Relation of power factor and solar radiation

The analysis of power factor in figure 9 shows a relation to solar radiation in zones A and C, reaching values of 0,94 p.u. and 0,96 p.u., respectively. ARCONEL Regulation 004/15 specifies that the power factor should be close to 1 with a variation of ±5 %. However, in zones A and C, this limit was exceeded and did not comply with the regulation requirements.

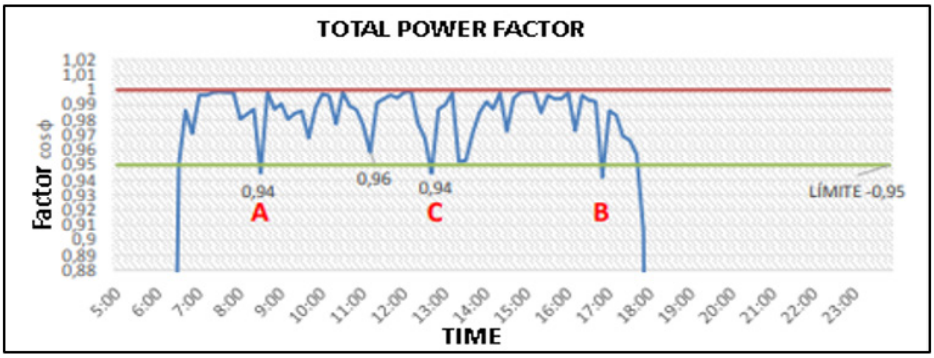

Figure 9. Power factor vs. Solar radiation

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Voltage vs. Solar Radiation

The voltage showed fluctuations in zones A, B, and C as can be seen in figure 10. In zone A, the voltage dropped from 13,070 kV to 12,935 kV in less than 20 minutes, with a slope of 6,75 kW/min. In zone B, the voltage reached 13,588V, varying from 13,588V to 13,035V in less than 20 minutes, with a slope of 27,6 kW/min. In zone C, the voltage changed from 13,527 kV to 13,015V in less than 20 minutes, with a slope of 25,6 kW/min.

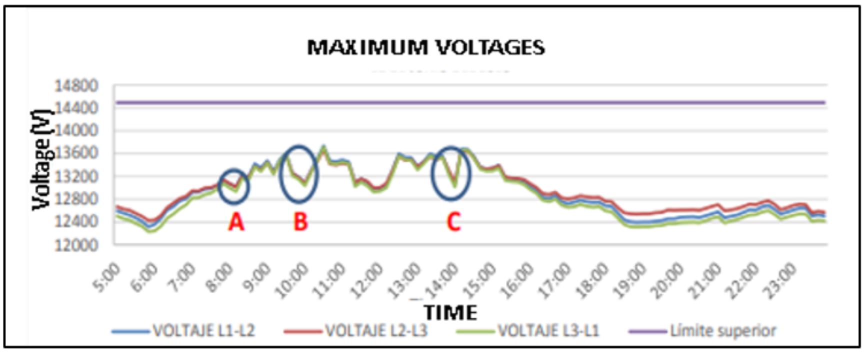

Figure 10. Voltage vs. Solar radiation

Total Harmonic Distortion of Voltage vs. Solar Radiation

The analysis in figure 11 of total harmonic distortion of voltage revealed no significant alterations in zones A, B, and C. Complying with Regulation 004/15 of ARCONEL, which establishes that voltage between (0,6KV≤ Vn < 40KV) must not exceed 6,5 %, the results remained below the established limit.

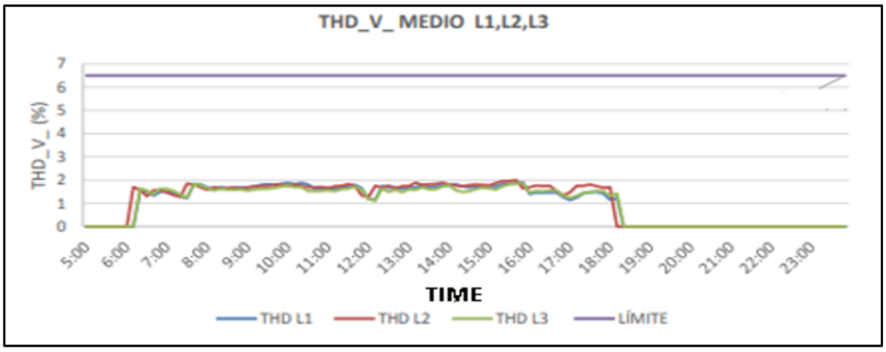

Figure 11. Total Harmonic Voltage Distortion (THD_V_) vs. Solar radiation

Flicker Pst vs. Solar Radiation

Significant increases in Pst were observed in figure 12 in zones B and C, while in zone A it remained at 0,35 p.u., within the allowed ranges according to the Regulation. In zone B, Pst reached a value of 2,7 p.u., varying from 0,35 p.u. in less than 20 minutes, and in zone C, it reached 2,5 p.u., changing from 2,5 p.u. to 0,35 p.u. in the same time period.

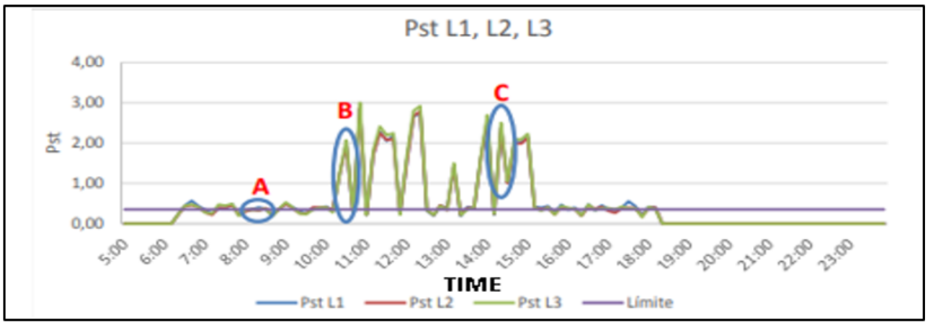

Figure 12. Flicker Pst vs. Solar radiation

Flicker Plt vs. Solar Radiation

An increase in Plt was observed in figure 13 in zones A, B, and C. In zone A, Plt remained at a value of 0,34 p.u. for two hours, failing to meet the allowed values according to the Regulation. In zone B, Plt reached a value of 2,10 p.u., varying from 0,67 p.u. in less than 20 minutes, and in zone C, it reached 1,92 p.u., changing from 1,92 p.u. to 1,46 p.u. in the same time period. According to Regulation 004/15 of ARCONEL, Plt should have a maximum value of 0,25 p.u., but in zones A, B, and C, the system exceeds this limit.

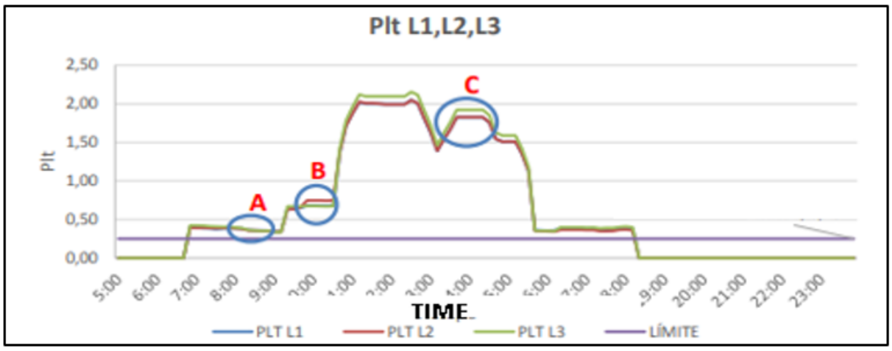

Figure 13. Flicker Plt vs. Solar radiation

Implementation of the Procedures Manual for Power Quality Improvement

The objective of the manual is to assist the Power Quality department of Emelnorte S.A. in making technical decisions to maintain current and voltage levels within the limits allowed by regulations ARCONEL 004/15 and the instruction "Determination of voltage bands and power factors of the interconnected national system S.N.I." through Alpachaca substation. The content of the manual provides technical personnel with the necessary information to analyze the power quality delivered by the "Parque solar Salinas" photovoltaic plant to the medium-voltage network of Emelnorte S.A through several tables with the "Parque Solar Salinas" data.

Table 5. General data of the Photovoltaic Plant "PARQUE SOLAR SALINAS"

Customer:Parque Solar Salinas	Type:Three-phase
Substation:Alpachaca	Power:100 KVA
Total Measurements:1008	Transformer No:C3T19
Location: Urcuquí-Imbabura-Ecuador	Feeder:M4

Table 6. Voltage registered of "PARQUE SOLAR SALINAS"

Voltage limits according to regulation 004/15			
Nominal voltage		270 [V]	
Upper Limit		297 [V]	
Lower Limit		243 [V]	
Rural		10 %	
REGISTERS		DATE	TIME
VLN1 máx.	291,224	13/06/2018	11:00:00
VLN1 máx.	258,632	16/06/2018	18:30:00
VLN2 máx.	290,032	13/06/2018	11:00:00
VLN2 máx.	260,976	16/06/2018	18:30:00
VLN1 máx.	290,932	13/06/2018	11:00:00
VLN1 máx.	256,966	19/06/2018	18:30:00

Table 7. Power factor register "PARQUE SOLAR SALINAS"

Power factor limit	0,95
Power factor average	0,86
Lower power factor	0,61
Upper power factor	1,00
Total measurements out of regulation	48,8 %

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Table 8. Register of Flicker Pst of "PARQUE SOLAR SALINAS"	
Upper limit of Flicker	1,00
Lower Flicker	0,163
Upper Flicker	3,83
Total measurements out of regulation (5 %)	32,24 %

Table 9. Register of Flicker Plt of "PARQUE SOLAR SALINAS"	
Upper limit of Flicker	1,00
Lower Flicker	0,00
Upper Flicker	3,29
Total measurement out of regulation (5 %)	49,50 %

The data shows that the voltages are within the limits set by Regulation CONELEC 004/15 for the quality of distribution electrical service. However, it is worth noting that the currents exceed the maximum limit around 11:40 due to the intensity of solar radiation. It is also observed that a significant percentage of measurements are outside the allowed limits of the regulation, which requires corrective actions. Additionally, the Plt values exceed the limit of 0,25, indicating the need to take measures to comply with regulations.

CONCLUSIONS

The variability in solar radiation causes abrupt changes in active power, reactive power, power factor, voltage, Pst, and Plt because of the results between the solar radiation and the other parameters. Additionally, the response time of the MPPT control causes significant variations in active power. The power quality at the point of connection was analyzed, and it was found that parameters such as Pst, Plt, and power factor exceeded the specified limits in Regulation 004/15 of ARCONEL. A comprehensive technical report was delivered to Emelnorte S.A., providing valuable information for future improvements.

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