







# Dry Transformer Specification for Photovoltaic Power Plants: Investigation into the K-Factor and the Use of 800VAC Disconnectors

Marcelo Esposito<sup>\*‡</sup>, Matheus Prestes Kunz<sup>\*ID</sup>, Gabriela Mesquita Bruel<sup>\*ID</sup>, Ana Belén Cristóbal López<sup>\*\*ID</sup>, Luis Fialho<sup>\*\*\*ID</sup>, Oumaima Mesbahi<sup>\*\*\*\*ID</sup>

\*Environmental and Sanitary Engineering, Federal University of Fronteira Sul Campus Erechim, ERS 135 - Km 72, 200, Cx Postal 764, CEP 99700-970, Erechim/RS, Brazil.

\*\*Instituto de Energía Solar, Universidad Politécnica de Madrid. C/Alan Turing S/N, 28031 Madrid, Spain.

\*\*\*Eurac Research, Institute for Renewable Energy, Bolzano, Italy.

\*\*\*\*Instrumentation and control Laboratory, CREATE, Department of Mechatronics, School of Sciences and Technology, University of Évora, Rua Romão Ramalho, 59, 7000-671 Évora, Portugal.

(marcelo.esposito@uffs.edu.br, matheus.kunz@estudante.uffs.edu.br, gabriela.brueel@estudante.uffs.edu.br, anabelen.cristobal@upm.es, luis.fialho@eurac.edu . omesbahi@uevora.pt)

‡ Corresponding Author; Marcelo Esposito, ERS 135 - Km 72, 200, Cx Postal 764, CEP 99700-970, Erechim/RS, Brazil., Tel: +55 (54)3321-7035,

Fax: +55 (54)3321-7035, marcelo.esposito@uffs.edu.br

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**Abstract-** Although there are several transformer manufacturers in Brazil dedicated to photovoltaic power generation, the connection between inverters with a nominal output voltage of 800VAC and the protection system installed before the step-up transformer is still complex. In this paper, issues related to design, installation and supply of equipment and preventive and corrective maintenance are explored. Operating data is presented for two photovoltaic plants (PV), one has a power of 444kWp and the other 406kWp, which share the same installation design. Both plants experienced faults including, in the worst case, a short circuit followed by a fire caused by the general disconnector. The transformers of 500kVA and K1 factor were assessed after the accidents and showed no faults in the measurements taken at the substations. The installation of disconnect switches with a nominal operating voltage ( $U_e$ ) equal to 690VAC was identified as the cause of the short circuit. The quality of the equipment was investigated and an analysis of the operating temperature of the transformers was carried out. Possible causes and effects, such as the presence of harmonics and inverter failures, were explored. Given the high cost of circuit breakers for 800VAC/400A  $U_e$  and transformers with a K4 factor, the solution found was to repair them and replace the faulty cables and switch-disconnectors with products dedicated to photovoltaic systems. The use of fuses in the AC circuit made the disconnection difficult and impaired the safety in several aspects.

**Keywords** Transformer, dry, photovoltaic, fuse, disconnectors.

## 1. Introduction

The environmental impacts of Utility Scale Solar Energy (USSE) systems occur at different rates and magnitudes throughout the lifespan of the plant, which can range from 25 to 40 years. These impacts include effects on biodiversity, water use and consumption, and air quality, among others [1].

According to Zidane et al. [2] transformers are crucial components of photovoltaic (PV) systems, essential for increasing the voltage generated by the photovoltaic modules to levels compatible with the electrical grid, in addition to providing the necessary galvanic isolation for system safety. Shimpf & Norum [3] assessed the evolution of transformer technology to meet the specific demands of renewable energy applications. The challenges include high weight, high cost, additional losses, and non-unity power factor in transformers operated at grid frequency. Another approach proposed by Shimpf & Norum [3] was the elimination of the transformer, resulting in transformerless inverters, which offer very high efficiencies, low weight, and lower costs. The authors, however, point out that the lack of galvanic isolation between input and output can pose safety risks, especially in the event of insulation failures in the photovoltaic generator or DC wiring.

Referring to the Technical Standard for the Connection of Distributed Micro and Mini-generation [4] in Brazil, all distributed mini-generation plants with power exceeding 75kW must be connected to the grid through a coupling transformer, which is under the consumer's responsibility. Additionally, this transformer must be protected by a circuit breaker that operates at medium voltage.

Energy losses in LSPVSS (Large Scale Photovoltaic Systems) are based on real failure probabilities. Baschel et al. [5] identified that the main factors contributing to the reduction in energy efficiency are the prolonged repair periods of transformers and inverters. Although transformer issues are extremely rare (less than 1%), they result in disproportionate energy losses due to the long time required to replace the equipment. Problems with transformers and inverters account for about two-thirds of the total energy losses in these systems.

Photovoltaic installations significantly affect low-voltage distribution networks, causing reverse power flows, voltage rises and fluctuations, variations in reactive power, and increased energy losses [6]. With the greater penetration of PV systems, the demand on the distribution feeder decreases, as part of the energy comes directly from the PVs, which amplifies voltage variations [6]. Distributed generation systems face power quality issues, such as voltage deviations and power flow reversals, which are common in low-voltage networks [6]. Unbalanced currents and asymmetric impedances can result in voltage imbalance, which can increase the voltage in two conductors and reduce it in the third, preventing damage to equipment [6]. High PV penetration can cause reverse flows, compromising the safety and reliability of the grid, as well as leading to overvoltages and increased losses [6].

The increasing use of direct current (DC) power distribution technologies, such as DC microgrids (MGs -

MicroGrids), offers superior performance in interruption, with faster and more reliable switching times, than traditional mechanical alternating current (AC) circuit breakers, which are effective for protecting AC circuits. However, the design of DC circuit breakers (DCCB - DC Circuit Breaker) poses considerable challenges, due to the need to quickly interrupt high fault currents within milliseconds, as these currents increase much more rapidly in DC networks than in AC networks [7].

In the study by Alhmoud [8], transformer losses are classified into iron losses and copper losses. Iron losses, or core losses, are constant and include hysteresis losses, caused by the repeated magnetization and demagnetization of the core, and eddy currents, which result from currents induced in the conductors by the alternating magnetic field [8]. To minimize these losses, low-hysteresis loss core materials such as silicon steel and laminated cores, which reduce eddy currents, are used [8]. On the other hand, the second kind of losses which are copper losses, occur due to the heat generated by the flow of current in the resistances of the primary and secondary windings, and can be minimized by using thick copper wires [8]. These strategies help increase the efficiency and reliability of transformers.

Since the early installation of photovoltaic systems, it has been common to use components and design processes from other electrical technologies, especially low-voltage AC systems. However, this approach is inadequate for photovoltaic DC circuits, which have distinct characteristics, such as low short-circuit current, a higher risk of electric arc and DC shocks [9]. Unlike AC circuits, DC circuits are more prone to forming electric arcs, they do not extinguish easily. Extra precautions are essential to prevent fires, such as proper terminal tightening and thermographic inspections [9]. Additionally, fuses are necessary to protect the system against overcurrent from the photovoltaic array [10].

The lack of proper grounding is also a significant concern. Once there is a virtual connection or the occurrence of a lightning strike, a ground fault may happen, which not only degrades the efficiency of power generation but can also lead to severe consequences, such as the burning of the string box [11]. According to Wu et al. [11], installation mistakes, poor photovoltaic modules, and DC arc ignition on the back sheet are the primary reasons of arc failure.

In the work conducted by Bakir & Marabet [12], significant changes in field automation infrastructure were implemented to improve power generation. These changes included the necessary configuration for remote reading of the RTU (Remote Terminal Unit) and the EQR (Energy Quality Recorder). In addition, changes were made to ensure the ability to control and monitor the medium voltage (MV) section, established with the power distribution company. These improvements enabled more accurate monitoring and more efficient control, resulting in more reliable and optimized power generation [12].

To reduce the Levelized Cost of Energy (LCOE) and total cost of ownership, large-scale solar plants use higher-capacity power blocks that integrate multiple inverters with a Low-Voltage/Medium-Voltage transformer and a medium-voltage

circuit breaker. These components are mounted on a metal structure called a SKID, which reduces installation costs and minimizes errors [13]. The inverter/transformer connection on the SKID is made via a busbar, which increases efficiency [14]. AC and DC protection varies depending on the manufacturer, including circuit breakers or contactors, with the option of additional protection according to local requirements [14].

The integration of photovoltaic systems into the power grid also presents challenges related to harmonics. The primary causes of these harmonics are the direct current (DC) side impedance of the inverter, methods of pulse width modulation (PWM), and weather fluctuations that impact the output current. Matre [15] claims that harmonics can lead to a number of detrimental problems with electrical systems, including overheating of machinery, large overvoltages, interference with protection and communication systems, and overloading of grid protection devices. Third-order harmonics also result in a significant rise in zero-sequence current, which increases the current in the neutral conductor.

According to Weller, Edwards, and Dalton [16], in recent years, one of the trends is the connection of photovoltaic generation into large industrial facilities. Typically, these locations already have significant harmonic content from variable speed motor drives and other non-linear loads, with these driving harmonic currents drawn into the filters of photovoltaic systems. International standards, such as IEEE 519-1992 [17], specify limits for voltage and harmonic current at the point of common coupling between the end user and distribution utilities. The European standard EN 61727 [18] establishes even more restrictive limits for voltage and current harmonics in photovoltaic systems.

In their study, Iaronka et al. [19] added that the waveform at the output of inverters can distort the magnetic field of the windings, thereby increasing losses and generating circulating direct current, which raises core induction and magnetizing current. Renewable energy transformers remain energized for them to always be ready to receive load with minimal effects of inrush current or magnetizing current. The maximum solar power generation occurs when the maximum ambient temperature is available, which increases the load and cooling challenges for transformers. Additionally, the typical harmonic spectrum can cause internal overheating due to the dispersed magnetic field.

Moreover, Iaronka et al. [19] observed that the employment of inverters in photovoltaic systems can lead to voltage and current imbalances on the secondary side of the transformer. This can lead to non-uniform heating, in which the windings and metallic parts overheat because of parasitic losses. Iaronka et al. [19] point out that the electrical system, including photovoltaic systems, can experience transient overvoltage and undervoltage. These variations may alter dielectric strength and cause transformer failures. Dry transformers according to Iaronka et al. [19] face mechanical stress due to thermal variation, which may weaken the insulating resin and lead to dielectric failures. The resin used as insulation must be thermally treated to withstand abrupt load variations, as the thermal expansion coefficient of the resin differs from that of the internal coil materials. Lack of

proper thermal treatment can result in cracks in the resin, compromising the dielectric insulation capacity.

Matre [15] suggests several methods to mitigate harmonics, including passive filters, inductive reactors, phase-shifting transformers, active filters, or multipulse converter sections. K-rated transformers are designed to withstand different levels of harmonic current without exceeding their specified temperature limits. The K-factor, which can range from 1 to 50, determines a capacity in which the transformer can handle harmonic load, with a K-factor of 1 used for linear loads and a K-factor of 50 recommended for severe harmonic conditions. The author in Matre [15] also mentions that the most common corrective measure for mitigating harmonics is the use of harmonic filters tuned to appropriate frequencies.

This paper presents experimental data from two photovoltaic (PV) plants: a 444kWp plant installed in the state of Santa Catarina, in southern Brazil, consisting of four 100kW inverters and 1096 monofacial and monocrystalline modules, and another plant installed in the state of Rio Grande do Sul, consisting of four 100kW inverters and 1004 monofacial modules, totalling 406.62kWp. The plants share the same ground installation design, including the substation, using a dry-lift transformer. The aim of this work is to scientifically and technically explore the reason for the occurrence of accidents at both plants, involving the dry-lift transformers and the disconnecting switches used in the substation. The operating time of the plants after commissioning was the same, approximately one year to the date of the accidents (March 8, 2022). The authors analysed the designs, the data provided by the transformer manufacturers, the reports from a reference company in transformer repair, who took the measurements without removing them from the substations and the manner in which the electrical circuits involved were assembled.

The photovoltaic energy sector recommends that the transformer be oversized to meet the need for a high K factor. This factor is related to the harmonic content of the signal. In the 406kWp plant, a 500kVA transformer with a K1 factor was used. Another guideline is that transformers should at least have a K4 factor and that, if possible, the SKID concept should be used: separating the DC circuit from the AC circuit, minimizing the plant's maintenance costs and compartmentalizing some equipment, such as inverters, AC protection, transformation and medium voltage metering.

From pure observation of the transformer at the 406kWp plant, during the period in which it was in operation until the days close to its shutdown, due to the risk of short-circuit and fire, the following problems were identified: when the transformer was first energized, which at the time was new, the protective fiberglass paint was peeling off and the temperature monitoring system showed incorrect measurements. Subsequently, the same transformer started to make an abnormal noise for a transformer in operation. It turned out that no screws or plates were loose, so these were electromagnetic losses, resulting in the shrill sound. The manufacturer's manual gives the following causes for noise above the permitted level: higher than expected voltage or uneven seating of the transformer base or resonance with surfaces around the equipment or resonances transmitted by

the connections. Operation at voltages above the nominal can cause saturation and a significant increase in losses, which can result in overheating and higher than normal noise levels.

The temperature in the substation room was consistent with that of a normally operating system. With the transformer's temperature indicator oscillating between 50 and 70°C, also in line with the solar radiation on the masonry room. At the time of shutdown, the temperature in the substation room, with the doors closed, was unbearable for humans. As for the sense of smell, on the day of the shutdown and the days before, no major changes were detected, not even the formation of smoke or anything similar, despite the excessive heat and the formation of stains on the floor formed by something like silicone under the transformer.

The company's report after the accident was imperative about the need for maintenance, with the recommendation to replace the insulation and windings of the medium voltage phases. If the low-voltage phases were also replaced, all that would be left would be the metal structure of the transformer under analysis. In the authors' opinion, the right thing to do is to send the transformer for bench analysis in a specific laboratory to identify possible damage. It should be ensured that after repair, it is able to withstand the harmonic content generated by the inverters,  $THD < 3\%$  (Total Harmonic Distortion), data supplied by the inverter manufacturer.

With regard to disconnectors, the authors detail the difficulties of working with the inverters' special nominal output voltage, which is 800VAC (3~ + Earth). The cost and lack of circuit breaker suppliers meant that they had to use 400ACA and 160ACA disconnectors, NH2, 350A fuses and NH000, 100A fuses, respectively. In the post-accident analysis, it was possible to identify that the fuse screws had loosened and changed colour without the fuse indicator changing from its original position. The key screws holding the fuse terminals, through which an electric current of up to 400A flows, were also loose and had changed colour, indicating a high temperature.

In the case of the 444kWp photovoltaic plant (PV), there was a cascade effect. The harmonic content severely affected the operation of the transformer and the worsening quality of the power transformation led to the sectionalizing switches collapsing with a short circuit, followed by a fire.

## 2. Materials and Methods

The chronology of the facts is extremely important in order to identify the storage and operating time of each piece of equipment. The 406kWp transformer arrived at the plant on February 17, 2021, from the manufacturer. It was completely installed in the PV substation on March 2, 2021. It was only energized on January 31, 2022, when the temperature measurement error was identified. According to Fig. 1, the damage to the fiberglass seems to indicate that something quite serious has happened to the transformer.

Fig. 2 shows the specification of the paint used by the company responsible for the installation to touch up the peeling paint. No more in-depth repairs or operational analysis

(of the taps) involving the transformation ratio between primary and secondary sides were carried out at the time.

According to Fig. 3 and 4, the transformer's S3 channel temperature sensor was replaced on May 19, 2022. After the replacement, the temperature sensor was not calibrated. While the temperature measured on S3 was 33°C, the temperature measured on the other channels was 48°C. The fault was identified when the temperature controller was energized for the first time on January 31, 2022.

In addition to the problems with the fiberglass structure and the defect in the temperature sensor, there were the items indicated by the reference company in transformer repair, according to the analysis report delivered on May 31, 2023: "with the data obtained and the evaluations made, this equipment should be sent to the manufacturer or accredited companies. The equipment should be subjected to new factory tests to confirm the faults found and then carry out the necessary repairs or even replace the medium-voltage coils. In this situation, we do not approve of energizing the equipment before the suggested repairs.". Fig. 5 shows the equipment used by the company to prepare the technical report on the transformer. The company was contacted after the plant was shut down (29/04/2023) because of two critical faults: the substation room had a temperature above that considered normal (around 40°C even at 2pm) and the sound emitted by the transformer was very different from normal. In addition, one of the fuses in the general disconnector was abnormally coloured, although it didn't indicate that it had been tripped.

The transformer in question does not indicate the K factor on its nameplate. On consulting the manufacturer, the answer was K1. The K factor is an international index that indicates a transformer's ability to withstand harmonic content in its load current and also remain within its temperature limits in order to work efficiently and safely. However, if the transformer's K factor is not in line with the harmonic currents in the installation, it will overheat, reducing the useful life of the equipment and compromising the entire network and the equipment connected to it. A low K factor accentuates the need to retighten screws in general and regularly clean the transformer and the environment in which it is installed (regular maintenance).

Regarding the non-conformities of the general disconnector in the inverter panel, a panel with 5 circuit breakers was installed on March 18, 2021. The manoeuvring and protection devices, called circuit breakers, were sized incorrectly, making it completely impossible to energize the PV. The small metal panel brought the copper bus dangerously close. The risk of arcing was obvious at a nominal voltage of 800VAC and an electric current of 320ACA. The use of PVC cable trays demonstrated the total ignorance of the assemblers and designers about the gauge of the cables to be installed. The installation of a neutral bus also contradicted the inverter installation circuit. Nominal voltage of 800VAC and maximum inverter output current of 80.2ACA, three-phase alternating current (AC) circuit, without neutral. Connection of the insulation resistance meter is shown in Fig. 5.

The first inverter switchboard (QGINV), shown in Fig. 6 and 7, was never energized and was eventually dismantled and

replaced with another one because the general circuit breaker had the following electrical characteristics: maximum rated current ( $I_n$ ) of 400ACA, rated operating voltage ( $U_e$ ) of 690VAC and rated insulation voltage ( $U_i$ ) of 800V. Circuit breakers with  $I_n$  of 100ACA,  $U_e$  of 690VAC and  $U_i$  of 800V had been used to protect the inverters. Surge protectors (SPDs) with  $U_c$  (maximum continuous operating voltage) of 680VAC, class 2 and maximum discharge current of  $45kA@8/20\mu s$  were also installed in series with 100ACA and 500VAC cylindrical fuses. It is important to clarify that the sizing error was partly due to the difficulty of finding equipment for the nominal operating voltage ( $U_e$ ) of 800VAC on the Brazilian market. In addition, no basic wiring diagram or descriptive memorial was drawn up for the QGINV, which the authors consider to be a fault on the part of the contracted design engineers. This technical data which, given its

importance, should be guarded for the safe operation of the plant during its 25 years or more of operation.

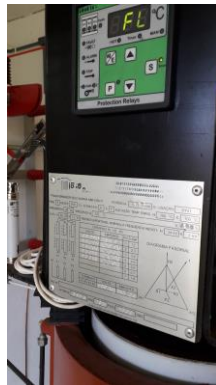
Only the SPDs were reused in the second QGINV shown in Fig. 8. In this new panel, switch-disconnectors were used for the inverters with  $U_e$  of 800VAC,  $I_n$  of 160ACA and  $U_i$  of 1200V, AC-22B load operating capacity, NH000, 100A, 800VAC fuses. For the main switch,  $U_e$  of 690VAC,  $I_n$  of 400ACA,  $U_i$  of 1000V and AC-22B load operating capacity, NH2, 350A, 800VAC fuses were used. The switch manufacturer declined to deliver the main switch because it is only sold commercially with a nominal voltage ( $U_e$ ) of 690VAC and a nominal insulation voltage ( $U_i$ ) of 800VAC, but the design engineers decided to use it. The incorrect installation of the main switch is thought to be the main cause of the accidents at the two PVs.



**Fig. 1.** The transformer installed in the substation of the 406kWp photovoltaic plant. As of the date of the image, 04/12/2021, it had not been energized, but already showed degradation of the fiberglass insulation.



**Fig. 2.** Paint used on 09/03/2022 to repair the transformer's fiberglass. The paint was applied directly to the damaged areas only. 406kWp photovoltaic plant.



**Fig. 3.** Temperature measurement failure on channel S3. Nomenclature indicated on the transformer's temperature controller on 31/01/2022. 406kWp photovoltaic plant.



**Fig. 4.** The S3 channel temperature sensor was replaced on 19/05/2022. 406kWp photovoltaic plant. The ambient temperature on the same date and time was 12.5°C (at the weather station installed near the substation).



**Fig. 5.** Insulation resistance meter.



**Fig. 6.** Internal image of the first inverter control panel.



**Fig. 7.** Internal image of the first inverter switchboard installed on 15/03/2021 at the substation of the 406kWp photovoltaic plant.



**Fig. 8.** Internal image of the second inverter switchboard installed on 16/03/2022 at the substation of the 406kWp photovoltaic plant.

### 3. Results and Discussion

In this case, involving electricity, the unpredictability of the improper use of electrical equipment outside the manufacturer's specifications stands out. This negligence caused material damage and losses due to the short circuit, environmental damage, such as the release of toxic materials, and could easily have affected human health.

On April 25, 2023, remote monitoring via software [20] did not indicate any faults in the 406kWp plant. As well as on previous dates that month, according to the temperature values shown in Fig. 9. On April 28, 2023, the substation room had a temperature above that considered normal and one of the fuses in the general disconnecter had a different colour, although it did not indicate that it had been triggered (Fig. 10). On April 29, 2023, it was decided that the PV should be completely shut down.

Grids that operate with nominal voltages in the range above 1000V and below 69kV are called medium voltage (MV) distribution systems. The transformer shown in Fig. 9 operates at voltage levels of 13.8kVAC with a medium voltage connection to the distribution network and at 800VAC, which is the nominal voltage of the inverters. With this information and for technical reasons, it is understood that any professional who is going to work in low voltage (LV) should have full knowledge of ABNT NBR 5410 [21] - Low Voltage Electrical Installations: in the case of components with no moving parts, such as fuses, conductors, busbars, rails, channels, connectors, terminals, transformers, etc., the general condition should be inspected, checking for signs of heating and drying out, as well as fixing, identification and cleaning. NOTE: The connections must be retightened no more than 90 days after the electrical installation is put into operation and repeated at regular intervals. NR 10 [22] - Safety in Electrical Installations and Services states that: the project description must contain at least the following safety items: g) a description of the compatibility of the protection devices with the electrical

installation. This document did not exist at the time of the so-called accidents.

Regarding medium-voltage operation (13.8kV), the standard to be considered is ABNT NBR 14039 [23] - Medium-voltage electrical installations from 1.0 kV to 36.2 kV: power transformers must be protected against internal defects, overloads and short circuits and, in certain cases, against ground insulation defects and overvoltages. Design issues to consider: every time the substation transformer at the 406kWp plant was energized, the medium-voltage circuit breaker at the primary substation tripped. Adjustments were made to the primary substation to meet the demands of the power utility, which did not prevent the medium-voltage circuit breaker from tripping.

The degree of severity of the short-circuit that was avoided at the 406kWp PV, but which occurred at the 444kWp PV (Fig. 11) can be measured indirectly by the number of faults indicated by the photovoltaic inverters. There are 4 inverters in each plant, all of the same model and power. Maintenance is a common and simple activity, which should be carried out using the plant's monitoring and diagnostics software (in this case, dedicated software called FusionSolar).

Tables 1 and 3 show the fault histories of the 406kWp plant's four inverters, from the moment they were first energized to the dates when they were shut down due to accidents on the QGINV board (the general board for the inverters installed in the plant's substation before the power transformer). In Table 2, the alarms "Grid loss" and, above all, "Grid undervoltage" and "Grid overvoltage" are strongly related to the operation of the transformer installed in the PV substation. All the alarms appear in the software as "Removed after fault recovery".

Situations associated with damage to equipment [24]. Sustained and temporary overvoltages: short-circuit in the secondary network; situations before and after protection (fuse). Opening or bad contact in a phase on the primary of the distribution transformer. Opening or bad contact in a phase of

a primary feeder section. Regulation problems/abnormal conditions in LV, MV or high voltage (HV) supplies of long duration.

Sustained and temporary undervoltages [24]: opening or bad contact in the phase of the secondary circuit. Short-circuit in the secondary network. Opening (open fuse or broken conductor) or poor contact on a phase in the primary. Temporary regulation problems and abnormal supply conditions.

Therefore, in addition to the transformer's low K factor (harmonics and heating considerations) and all the problems indicated in the transformer's technical report (cracks found in the epoxy coils, the need for a thorough cleaning of the equipment, etc.), the heating of the general disconnecter must also be taken into account. The heating of the disconnecter (change in color of one of the fuses) may have caused overvoltage or undervoltage (sometimes one, sometimes the

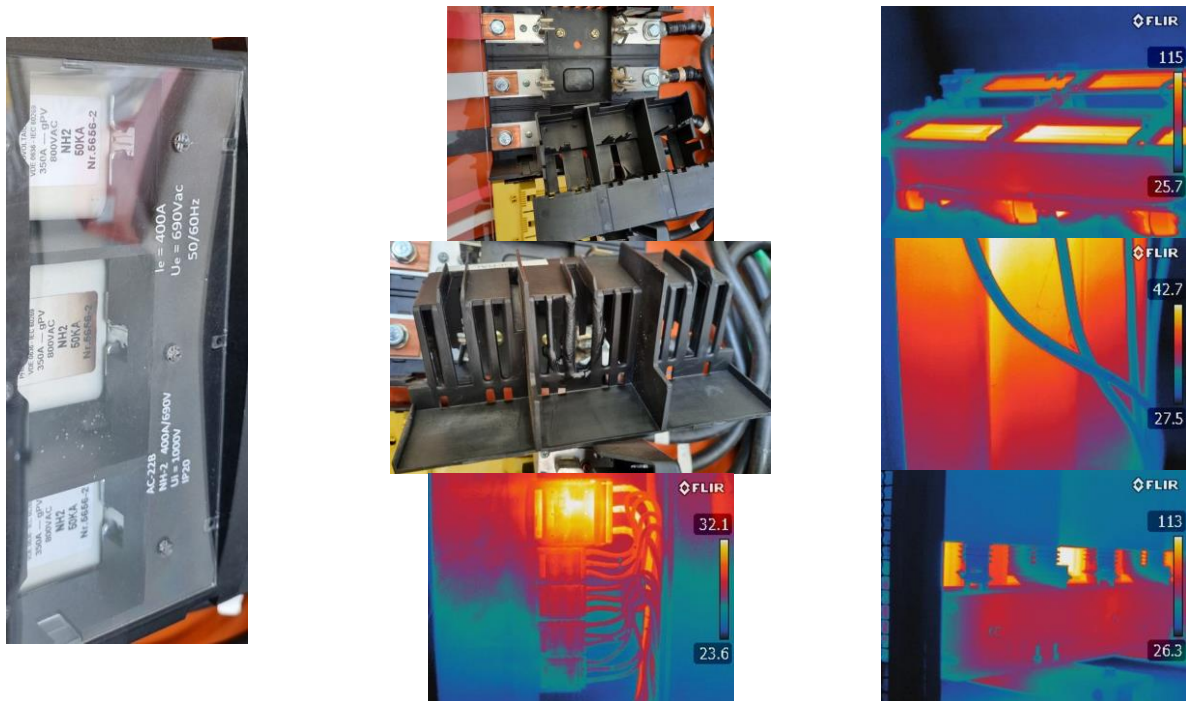
other), as presented in Kagan et al. [24] (opening or bad contact in a phase).

The conclusion is that the transformer should be sent to the factory for laboratory testing if it is going from the utility grid into the plant. The QGINV panel must at least comply with current standards, with a complete project comprising diagrams, calculation and sizing reports, etc.

A new commissioning will have to be carried out, as there is a remote possibility that the photovoltaic inverters have been affected in some way by transients involving their output voltage and/or current (alternating current). Commissioning must strictly follow the ABNT NBR 16274 [25] standard.



**Fig. 9.** Thermography of the QGINV on 19/05/2022 at 16h and 30 min in the 406kWp plant. Thermal image of the transformer on the same date and time. The ambient temperature on the same date and time was 12.5°C (at the weather station installed near the substation).



**Fig. 10.** On 29/04/2023, at 6pm, the 406kWp plant was disconnected from the grid. Fuse coloured differently from the others in the general disconnecter. Record of the start of melting of the general disconnecter on the white busbar. Thermography of the top, middle and bottom of the transformer on the same date and time. The ambient temperature on the same date and time was 21.3°C (at the weather station installed near the substation).

**Table 1.** Fault history from 28/06/2022, when the first ID was detected on 27/03/2023, to when the last fault record was identified before the 406kWp plant was shut down on 29/04/2023. The plant went into operation on 07/03/2022.

27/03/2023 11 faults	22/03/2023 1 fault	21/03/2023 1 fault	13/03/2023 1 fault	12/03/2023 9 faults	12/02/2023 1 fault
07/02/2023 15 faults	04/02/2023 4 faults	19/01/2023 1 fault	27/12/2022 17 faults	26/12/2022 29 faults	14/12/2022 1 fault
22/11/2022 4 faults	21/11/2022 1 fault	14/11/2022 4 faults	08/11/2022 1 fault	31/10/2022 1 fault	16/10/2022 4 faults
02/08/2022 2 faults	16/07/2022 3 faults	12/07/2022 1 fault	28/06/2022 13 faults		

**Table 2.** Distribution of alarms throughout the 406kWp plant's operating time.

ID of alarm	N° of times	Name of alarm	Gravity of alarm	
1	2013	4	Abnormal energy in the string	Warning
2	2032	63	Network loss	Principal
3	2033	37	Grid undervoltage	Principal
4	2034	7	Grid overvoltage	Principal
5	2064	3	Device failure	Principal
6	999999999		Abnormal communication	
Total	114	Without adding up the 11 faults ID 999999999 - Abnormal communication		

**Table 3.** Inverter serial number and number of faults recorded. 406kWp plant.

Inverter serial number	Project	Quantity of faults - IDs	
2101074242ESK6000103	I1 - Inverter 1	26 faults	16 times ID 2032; 10 times ID 2033
2101074242ESK6000126	I2 - Inverter 2	25 faults	16 times ID 2032; 9 times ID 2033
2101074242ESK6000174	I3 - Inverter 3	26 faults	16 times ID 2032; 9 times ID 2033; 1 time ID 2034
2101074242ESK6000123	I4 - Inverter 4	37 faults	15 times ID 2032; 9 times ID 2033; 6 times ID 2034 4 times ID 2013; 3 times ID 2064



**Fig. 11.** On 02/05/2023, the main switch installed in the 444kWp photovoltaic plant caused a short circuit followed by a fire in the plant's substation. One of the fuse links did not break, leaving the three-phase circuit energized after the incident.

A photovoltaic module called I4S7 (inverter 4, string 7) in the PV's single-line diagram, which probably came from the factory with faulty by-pass and/or blocking diodes, caused an entire string to be inoperative from the first day of the plant's operation until the day it was shut down due to the general disconnecter. This damaged module should have been

identified and replaced during commissioning on 07/03/2022. Another fact is that the fault indicated by the inverter as ID 2013 may be directly related to the defect in the I4S7 photovoltaic module, i.e. if the faults had been observed during preventive maintenance, which did not happen, this could have been identified and resolved safely.

Because of the faults ID 2034, ID 2013 and ID 2064 that occurred in inverter 4, this is more likely to have been affected by the lack of maintenance. As the other faults occurred almost equally (type and number of times) in the 4 inverters, it can be concluded that the alternating current part of the circuit had some serious problem. It is on this circuit that the

general disconnector and transformer for the plant's substation are installed.

Given the high number of faults (Tables 4 and 5) that occurred on the day of the short circuit in the main switch, it is likely that the electronic circuitry of the inverter(s) was damaged.

**Table 4.** Fault history from 30/06/2022, when the first ID was detected on 02/05/2023, to when the last fault record was identified. This last date corresponds to the day on which the accident occurred and, therefore, the 444kWp photovoltaic plant was shut down. The plant went into operation on 11/04/2022.

02/05/2023 73 faults	29/04/2023 1 fault	20/04/2023 2 faults	12/04/2023 4 faults	08/04/2023 1 fault	30/03/2023 1 fault
23/03/2023 3 faults	22/03/2023 1 fault	20/03/2023 1 fault	11/03/2023 5 faults	07/03/2023 1 fault	28/02/2023 1 fault
21/02/2023 1 fault	29/01/2023 1 fault	21/01/2023 10 faults	18/10/2023 4 faults	16/11/2022 4 faults	03/11/2022 1 fault
29/10/2022 4 faults	25/10/2022 1 fault	22/10/2022 15 faults	27/09/2022 2 faults	10/09/2022 1 fault	21/08/2022 16 faults
29/07/2022 8 faults	28/07/2022 1 fault	25/07/2022 1 fault	24/07/2022 1 fault	23/07/2022 1 fault	16/07/2022 2 faults
15/07/2022 1 fault	30/06/2022 19 faults				

**Table 5.** Inverter serial number and number of faults recorded. 444kWp plant.

Inverter serial number	Quantity of faults - IDs	
21010742426TK4900135	42 faults	21 times ID 2032; 7 times ID 2033; 13 times ID 2034; 1 time ID 2037
21010742426TK4900181	39 faults	18 times ID 2032; 7 times ID 2033; 12 times ID 2034; 2 times ID 2064
21010742426TK4900200	37 faults	19 times ID 2032; 6 times ID 2033; 12 times ID 2034
21010742426TK4900195	40 faults	21 times ID 2032; 7 times ID 2033; 12 times ID 2034
Total	158	Without adding up all 30 faults ID 999999999 - Abnormal communication

Tables 6, 7 and 8 show a quantitative assessment of the functionality of the dry transformers in terms of possible insulation faults or current leakage in the equipment. Both transformers were manufactured in 2021, with a K1 factor. In June 2023, safety and grounding procedures were carried out in the substations and on the equipment in order to carry out the assessments and visual inspections regarding cleanliness, possible visible faults, photographic records and measurement of the transformation ratio, the electrical resistance of the windings and the insulation.

It is not possible to compare the values of the transformation ratio and the electrical resistance of the windings between the transformers, as they are equipment from different manufacturers. The 444kWp transformer at the power station was manufactured by a multinational company that has been operating in this market since the 1980s and should therefore be of better design and construction quality, but this was the transformer affected by the short-circuit in the disconnector.

Table 6 shows the three-phase transformation ratio values of the transformers measured after the accidents without

removing the transformers from the respective substations. Table 9 shows the values supplied by the manufacturer of the 406kWp plant transformer. In these tests, the voltage ratio reached 0.38% at the 14490V tap and 0.00% at the other taps, meeting the ABNT NBR 5356 [26] standard ( $\pm 0.5\%$ ).

A complex situation has arisen, in which the engineer responsible for maintenance must choose whether to consider the transformation ratio values measured in the laboratory at the factory or those measured at the substation. Both transformers were damaged, if the data in Table 6 is taken into account. The plant's 406kWp transformer was shut down in normal operation, except for the temperature and noise issue analysed above. It is therefore necessary to assess the general context, such as the quality and reliability of the transformer, the uncertainty of the measurements taken with the HMTTR-2000 equipment, the alarms signalled by the inverters, the visual inspection of the transformer, and then decide whether to send it in for repair with new measurements taken in an accredited laboratory. The quotes requested show the need to remove the transformer to the laboratory, the cost of repair, if this is possible, transportation back to the substation and the

dismantling and assembly labour. With the exception of the original manufacturer, the others won't accept the faulty transformer as part of the payment, and since no copper is used, the value of the aluminium and steel scrap is greatly reduced. That said, it is financially more advantageous to dispose of the old transformer, sell it for scrap and buy a new one with the K4 factor specification.

Comparing the values shown in Table 7, which refers to the electrical resistance of the windings, with the corresponding values in Table 9, we can see the difference between the value measured at the factory (H: 5.980Ω; 5.980Ω; 5.975Ω) and that measured at the substation (H: 17.53Ω; 17.51Ω; 19.20Ω, respectively). The values for low voltage were not measured at the highest voltage, but at 18.3kV, making direct comparison impossible. Another fact is that the ambient temperature was not recorded at the substation and this represents a measurement error.

The company responsible for taking the measurements and preparing the reports opted for a test voltage of 5kV for measuring insulation resistance (Table 8). This is a far cry from the nominal values of 13.8kV/800V and 23.1kV/800V. No justification or standard was provided, such as ABNT NBR 5356-11 [26]. Power transformers; Part 11: Dry-type transformers - Specification; nor correction data related to ambient temperature, such as that used to verify the electrical safety and performance of the photovoltaic installation with HT-Instruments PVCHECKs equipment. It only presented a calibration certificate for an ambient temperature of 23°C±5°C, humidity of less than 70% and test voltages of 1kV and 5kV.

The routine test report supplied by the transformer manufacturer, in the section dealing with the dielectric test, gives the following information: insulation resistance at 2.5kV: H-(X) equal to 1TΩ, H-(Structure) equal to 1TΩ and X-(Structure) equal to 11GΩ. Temperature rise in the HV and LV windings equal to 100°C.

**Table 6.** Measurement of the transformation ratio on all transformer taps. Measurement carried out with the transformers installed in their respective substations after the damage caused by the disconnecting switches. Transformer turns ratio meter - HMTTR-2000.

13,8kV/800V - 500kVA – Photovoltaic plant of 406kWp				23,1kV/800V - 500kVA - Photovoltaic plant of 444kWp			
Switching Position	PHASE (A) H1	PHASE (B) H2	PHASE (C) H3	Switching Position	PHASE (A) H1	PHASE (B) H2	PHASE (C) H3
1) 14490V	31,480	31,100	31,330	1) 24200V	51,890	51,940	51,920
2) 14145V	30,200	30,220	30,170	2) 23100V	49,550	49,590	49,550
3) 13800V	29,410	29,430	29,390	3) 22000V	47,190	47,210	47,220
4) 13455V	28,650	28,660	28,630	4) 20900V	44,770	44,830	44,810
5) 13110V	27,860	27,870	27,860	5) 19800V	42,430	42,460	42,410
Nominal value	ABNT NBR 5356 [26] (±0,5%)			Nominal value	ABNT NBR 5356 [26] (±0,5%)		
31,372	-0,34%	-0,87%	-0,13%	52,394	-0,96%	-0,86%	-0,90%
30,625	-1,39%	-1,34%	-1,51%	50,013	-0,93%	-0,85%	-0,93%
29,878	-1,57%	-1,50%	-1,63%	47,631	-0,92%	-0,88%	-0,86%
29,131	-1,65%	-1,62%	-1,72%	45,250	-1,06%	-0,93%	-0,97%
28,384	<b>-1,85%</b>	-1,81%	<b>-1,85%</b>	42,868	-1,02%	-0,95%	<b>-1,07%</b>

**Table 7.** Measurement of the electrical resistance of the windings. Measurement carried out with the transformers installed in their respective substations after the damage caused by the disconnect switches. Winding ohmic resistance meter (Kelvin bridge) PK230.

13,8kV/800V - 500kVA - Plant of 406kWp						
Switching Position	H1-H3 (Ω)	H1-H2 (Ω)	H3-H2 (Ω)	X0-X1 (Ω)	X0-X2 (Ω)	X0-X3 (Ω)
1) 14490V	19,20	17,53	17,51			
2) 14145V	18,71	17,20	17,60			
3) 13800V	18,30	16,90	16,15	10,93	10,53	9,90
4) 13455V	17,82	16,84	16,60			
5) 13110V	17,20	16,65	16,01			
23,1kV/800V - 500kVA - Plant of 444kWp						

1) 24200V	121,0	116,0	110,7			
2) 23100V	106,0	107,8	113,0			
3) 22000V	98,5	97,4	101,0	112,0	102,3	111,9
4) 20900V	91,0	96,0	94,0			
5) 19800V	87,5	87,0	86,1			

**Table 8.** Measurement of insulation resistance at medium voltage (MV) and low voltage (LV). Measurement carried out with the transformers installed in their respective substations after the damage caused by the disconnecting switches. 10KV digital megohmmeter - HMMG-10.

Connexion	Plant of 406kWp		Plant of 444kWp	
	Resistance (MΩ)	Test voltage	Resistance (MΩ)	Test voltage
MT - GROUNDING	48	5kV	40	5kV
BT - GROUNDING	20	5kV	9,6	5kV
MT- BT	21	5kV	35	5kV

**Table 9.** Routine test report, three-phase dry transformer.

Voltage ratio test – Plant of 406kWp				
TAP (V)	PHASE 1	PHASE 2	PHASE 3	
14490	18,181	18,182	18,180	
14145	<b>17,681</b>	17,681	17,681	
13800	<b>17,250</b>	17,250	17,250	
13455	<b>16,819</b>	16,819	16,819	
13110	<b>16,388</b>	16,388	16,388	
Ohmic resistance test (Ambient temperature 25°C)				
	H1-H2 (Ω)	H2-H3 (Ω)	H3-H1 (Ω)	
H: 14490	5,980	5,980	5,975	
	X1-X2 (Ω)	X2-X3 (Ω)	X3-X1 (Ω)	
X: 800	0,005	0,005	0,005	
Short-circuit losses and impedance at 120°C				
Winding losses (W)	Core losses (W)	Total losses (W)	Impedance (Ez: %)	
5571	1800	7371	5,50	
Terminals AT/BT	H: Delta	X: Star		

The transformers were subjected to a thorough assessment with on-site tests. There was a lot of dirt and dust deposited on them, as well as all over the inside of the substations, which is highly detrimental to the operation of the transformers. Especially in the case of dry equipment, which must operate without the presence of contaminants. Although the measurements show satisfactory results, in the case of the 406kWp plant, the medium-voltage coils show visible flaws in the epoxy resin (Fig. 12 and 13), which could lead to an electrical discharge at these points, a risk of accident for those involved in energizing the equipment or irreversible damage to the rest of the transformer. Before energizing the transformer again, the coils must be repaired or replaced and then tested by an accredited laboratory.

In the case of the 444kWp plant, there was a visible flaw in the epoxy resin of one of the coils and a dark spot on the low-voltage insulation in one of the phases (Fig. 14 and 15). After further laboratory tests, the transformer was approved by a report and could be put into operation.

Fig. 16 and 17 shows the floor plan of the substations built at the 406kWp and 444kWp plants. The design complies with the transformer manufacturer's requirements: 0.5m between the transformer and the walls. The two 1.6m wide by 0.5m high openings are located 1.8m off the ground. This configuration does not meet the basic installation requirement: cold air inlet at the bottom of the transformer and outlet located at the top.

The substation's steel entrance door is 2.2m wide by 2.10m high and is not perforated, blocking air from entering. On the other hand, the buildings are on open ground, without obstacles, with an average wind speed of 2.5m/s all year round, an average annual temperature well below 40°C and an altitude of 700m above sea level.

Considering the total losses at 120°C (Table 9) of 7.371kW and the distance measured between half the height of the transformer and half the top air outlet of approximately 0.75m, the manufacturer estimates that the opening should be around 2.6m<sup>2</sup>. The upper openings total only 1.6m<sup>2</sup>. The total area of the building is 18.8m<sup>2</sup>, with a ceiling height of 2.8m. Considering the air volume inside the substation of 53m<sup>3</sup> and the existence of a temperature monitor during normal operation of the transformer, the need for artificial ventilation was not identified.

However, due to the accidents that have occurred and the solar irradiation on the building, especially in the summer, measures will be taken to increase the ventilation required to properly cool the transformer, increase the cooling capacity and prevent the transformer from overheating. All the inverters are installed under the rows of modules because they are IP65 rated. For this reason, they do not appear on the substation floor plan.



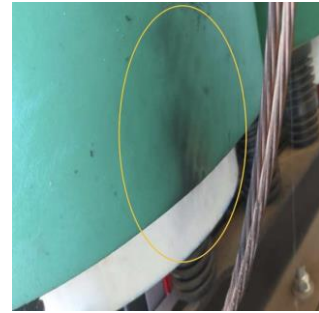
**Fig. 12.** Dust and coil failure. 406kWp power plant.



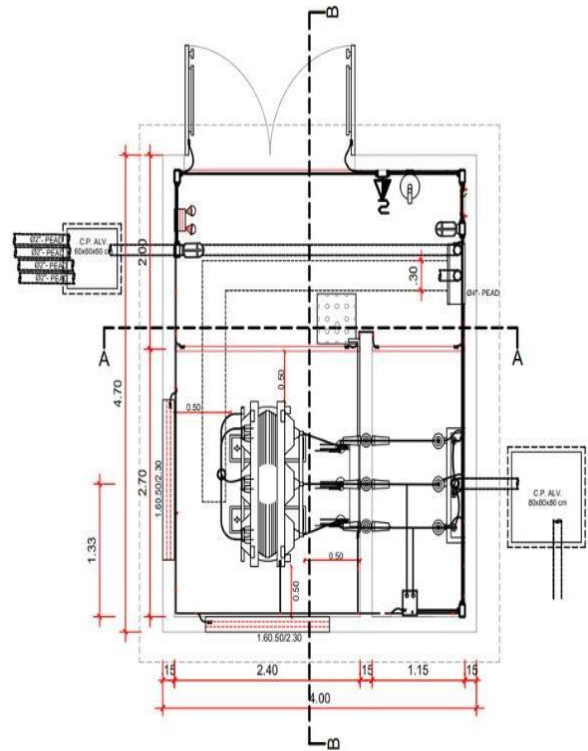
**Fig. 13.** Crack in the epoxy resin insulation. 406kWp plant.



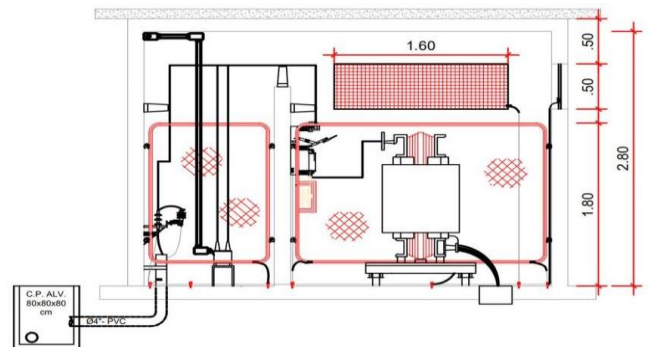
**Fig. 14.** Faulty resin or surface paint and cracked insulation. 444kWp plant.



**Fig. 15.** Dark spot on low-voltage insulation. Partial discharge. 444kWp plant.



**Fig. 16.** Floor plan of the substations built in the 406kWp and 444kWp plants.



**Fig. 17.** Section AA of the floor plan of the substations built at the 406kWp and 444kWp plants.

#### 4. Conclusion

From contact with various transformer manufacturers, it emerged that special projects, such as those involving an inverter output voltage of 800VAC, are selective factors when it comes to identifying suppliers. Another difficulty is precisely the use in photovoltaic systems, as not all manufacturers make it clear that due to the renewable energy source, it is necessary to use a K4 factor or higher. This is because the monetary cost usually doubles. The use of SKIDs with a complete, transportable, factory-tested infrastructure, developed with the aim of concentrating various devices such as the transformer, inverters, protection and control panels and communication systems in a single location, is recommended by the authors of this work.

The cost of designing and building the substation and purchasing the transformer, insulators, terminals, lightning rods, supports, rigid copper conductors, conduits, flexible cables of various gauges and purposes, metal frames, a wide range of electrical supplies, specific low and medium voltage equipment such as disconnectors and fuses, plus the cost of special tools and skilled labor, certainly exceeds the cost of purchasing a SKID for the same application.

Based on the results obtained, the need to increase the cooling capacity of the substation's internal environment was identified. As a result of this analysis, another possible source of failure was identified. The general switch-disconnector that caused the accidents was housed inside a metal frame 1.2m high, 0.8m wide and 0.35m deep, completely closed. According to the manufacturer of the disconnect switches, TES690-02, THS and TES800-00, THS, the maximum working temperature is +55°C. This method of installation has certainly reduced the useful life of the switches. Exhaust fans must be installed on the door of the inverter control panel (QGINV).

Only in 2022 did the manufacturer ABB present certification (IECEE Certificates) for the product line "800VAC Fusegear for string inverter protection - ABB's fusegear with improved performance is ready for the trend towards higher voltages up to 1000 VAC in photovoltaic installations". In this work, the solution found was to replace the disconnect switches with ABB models, codes XLP00-6BC 1SEP101890R0002 and XLP2-6BC 1SEP101892R0002, both AC-22B for 800VAC (ambient temperature range - 25...+55°C). The 12 fuses, size NH00 for use in the XLP00 100A/800VAC disconnector and the 3 fuses, NH2 for the XLP2 350A/800VAC are easily found on the Brazilian market, but of uncertain quality. NH fuses for photovoltaic systems, but generic ones, cost 5 times less than those from reliable brands.

The analysis of the alarms found in the inverter supervisory system and the design and execution error when using switches with a nominal operating voltage ( $U_e$ ) equal to 690VAC served as the basis for changing the disconnectors in the inverter switchboard. Various tests will be carried out with the 406kWp plant's transformer energized after the switches have been replaced and before it is sent for repair or replaced with a new one with a K4 factor or higher. In the case of the 444kWp plant, the implications of the short-circuit will still be

unravelling at the next energization and commissioning of the respective photovoltaic plant.

The photovoltaic inverter's functionalities were exploited to the full, such as the use of Huawei's "Smart I-V Curve Diagnosis" function to replace the use of IxV curve tracers such as the SOLAR I-Ve, 1500V, I-V curve tracer, HT Instruments [20, 27-35].

Alarm and fault monitoring was used in a similar way to the data provided by a power quality analyzer, such as the Fluke 435-II model, Power and Power Quality Analyzer. Functions such as dips and swells, harmonics, unbalance and inrush are lost. However, the data from the inverter's supervisory system serves as a basis for an experienced professional to identify the need to expand the analysis.

High-quality inverters will not connect to the grid if the insulation on the DC side fails. To ensure the safety of the device, the SUN2000-100KTL-H1 (Huawei/WEG) detects the insulation resistance between the input side and ground when it starts a self-check. If the detected value is lower than the preset value, the SUN2000 will not export power to the grid. Protection parameter "Insulation resistance protection threshold ( $M\Omega$ )". Low insulation resistance, alarm ID 2062. Abnormal grounding, alarm ID 2061. The output of the SUN2000-100KTL-H1 does not connect to an isolation transformer when the output of the PV string is grounded. Therefore, for the present work, the authors have not identified the need to use, for example, the PV CHECKs full PV tester, HT Instruments.

This detailed information leads to the conclusion that photovoltaic inverters have yet to incorporate functions that enable them to identify faults on the AC side. String boxes, with fuses and SPDs, on the DC side were not installed in the plants presented because these protection functions are built into the inverter (AC Overcurrent Protection, DC Surge Arrester Type II, AC Surge Arrester Type II, DC Insulation Resistance Detection, Residual Current Monitoring Unit), as are two DC switches. The manufacturer's manual states: "A three-phase AC switch must be installed on the AC side of the SUN2000. To ensure that the SUN2000 can be safely disconnected from the mains when an exception occurs. Select the appropriate overload protection device in accordance with local power distribution regulations."

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