10134
A3 – Transmission and Distribution Equipment
PS3 – Digitalisation of T&D Equipment

Real-time Leakage Current Measurement System Applied to LT 230 kV Insulators

Daniel de Andrade USSUNA[1]*, Renatto Vaz CARVALHO[1], Vitoldo SWINKA FILHO[1], Edilson Jose FRESHI[1], William César FARIAS[1], Guilherme Cunha da SILVA[1], Marcio TONETTI[2]
1 Instituto de Tecnologia para o Desenvolvimento - LACTEC
2 Companhia Paranaence de Energia Elétrica – COPEL G&T
Brazil
daniel.ussuna@lactec.org.br

SUMMARY

The insulator is one of the main power equipment used in transmission lines (TLs) and distribution lines (DLs) to provide mechanical support for the conductors, in addition, it presents high resistance to the conduction of current between the energized and grounded parts of the electrical system. This equipment must also withstand total disruptive discharges of the air (flashovers), resulting from overvoltage and conductive pollution deposited under the dielectric surfaces. The leakage current analysis as a technique for monitoring the electrical condition of the surface of power insulators presents itself as the most widespread form of analysis for this purpose, considering that the current signal is directly related to the electrical activity in the surface layer of this equipment. Therefore, this characteristic is considered adequate for laboratory and field analysis of power isolators. Leakage current data is used to monitor the performance of insulators to minimize faults in the electrical system attributable to pollution and this technique is applied to TLs and DLs exposed to high and varying levels of pollution. When critical leakage current levels are reached in polluted insulators, preventive maintenance is started, however, this technique needs constant supervision to analyze the condition of the insulators being monitored. The application of parameterized software for this purpose favors the optimization and performance of network maintenance teams so as not to need a specialist for data analysis. In order to generate a tool to monitor the leakage current of TL insulators, this work presents the development, laboratory and field application of an online measurement system for the leakage current of power insulators, for the purpose of diagnosing the operating status of these insulators, serving network maintenance teams, in order to optimize periodic interventions and minimize the concessionaire's operational risks. The sensors developed have a detachable core for installation on the insulator's anchoring pin, thus facilitating their application and allowing installation in an energized line. It has autonomous power supply, wireless remote communication and cloud software. The system has been validated in the laboratory and in the field for the range of 100 µA to 10 mA effective at 60 Hz, demonstrating that the instrumentation is immune to external electromagnetic interference at nominal voltages of the TL. Was applied in the field in 3 insulator chains of a 230 kV TL in the metropolitan region of Curitiba in the state of Paraná-Brazil. The installation of this system in TLs and DLs allows us to infer the ideal moment for maintenance on these equipments, optimizing its useful life and reducing technical losses in the electric power system, in addition to assigning intelligence for the analysis and diagnosis of network equipment in real time under the concept of Smart Grids.

KEYWORDS

High voltage insulators; Leakage current; Measurement system; Pollution; Transmission and distribution lines; Smart grids.

1.0 INTRODUCTION

Leakage current analysis as a technique for monitoring the electrical condition of the surface of power insulators is the most widespread form of analysis, given that the current signal is directly related to the electrical activity in the surface layer of these electrical system equipment [1,2].

This indicator of the state of degradation and/or the level of pollution deposited on the surface of transmission (TL) and distribution (DL) line insulators has been shown to be of great importance for maintenance activities of the electrical system, such as the definition of optimal cleaning time, replacement of insulators, among other forms of intervention in the network.

The insulator is a power equipment applied to provide mechanical support for overhead conductors, in addition to having high resistance to the passage of current between the energized and grounded parts of the electrical system. This equipment must also withstand total disruptive discharges of air (flashovers), resulting from overvoltage and conductive pollution deposited under the dielectric surfaces [3]. The main design parameter of power insulators is their flow distance, that is, the surface distance between the connections at the ends of the insulator, where this parameter is determined based on the maximum contamination levels estimated at each insulator application site [4].

The leakage current of an insulator is mostly made up of loads moving across the surface of the material, since the capacitive component of the impedance of these devices is insignificant at the industrial frequency of 60 Hz, when compared to the resistive component [3].

In the presence of moisture and pollution, there is a reduction in the surface resistivity of the dielectric material (glass, porcelain or polymer) and, consequently, a reduction in insulation resistance and an increase in the amplitude of the leakage current. In turn, the increase in leakage current can result in flashovers that can trigger the protection that stops the supply of electricity to the final consumer and worsens the utility's power quality indicators.

The leakage current signal from the insulators intensifies when the layer of pollution deposited on the surface of the insulator is moistened to a level of 75% or higher, during exposure of the insulator to precipitation or mist, as it results in the formation of electrolytic conductors [4, 5].

Leakage current data is used to monitor the performance of insulators to minimize electrical system failures attributable to pollution [6,7]. This technique is applied to TLs and DLs exposed to high and variable levels of pollution. When critical levels of leakage current are reached in the polluted insulators, preventive maintenance is started, however, this technique needs constant supervision to analyse the condition of the insulators being monitored. The application of parameterized software for this purpose favours the optimization and performance of network maintenance teams so as not to need a specialist for data analysis.

The biggest challenge of this type of analysis in an insulator in the field is the noise associated with the main signal [1], as the leakage current signal has an amplitude close to that of the noise signals, it is necessary to develop techniques for monitoring the separation of the signals of interest. To overcome this problem, combinations of different mathematical techniques were developed, such as the separation of signals from peak thresholds [8]. The literature identifies possible current limits that identify the operating status of the insulators, between 50 nA to 2.5 mA, with direct dependence on the type of insulating material. However, incorrect determination of this limit can either eliminate signals containing electrical activity or result in the storage of noisy information [4,6,7,8,9].

In order to minimize technical problems, the maintenance of the insulator cleaning is currently scheduled periodically by the concessionaire, based on local pollution studies. However, it is not possible to assertively state that a polluted insulator has a high leakage current so that this type of intervention is necessary. This test can only be performed by directly measuring this electrical quantity.

In addition to favoring the occurrence of flashovers that can paralyze the energy supply, the increase in leakage current also represents technical losses that must be accounted for by the utility.

In order to generate a tool to monitor the leakage current of TL insulators, this work presents the development and validation of a system composed of sensors, instrumentation, remote communication and software that operates in the measuring range within the range that serves from insulators new and clean up to insulators with a high degradation state. Therefore, this new system can be applied by electricity concessionaires in order to optimize their assets, reduce technical and operational losses, in addition to attributing new concepts in the sector related to Smart Grids, since data from the transmission sector can feed back systems information integrated to electrical systems that had been little explored until then.

The main results of the characterization of energy insulators with polymeric coatings applied in the laboratory are also presented, as well as the field application to collect real data. This new developed system proved to be assertive and free from external electromagnetic interference, validated in LTs of up to 230 kV, and can become a product manufactured and marketed on a large scale to meet the needs of energy concessionaires that carry out regular maintenance activities in networks from areas of high concentration of pollution.

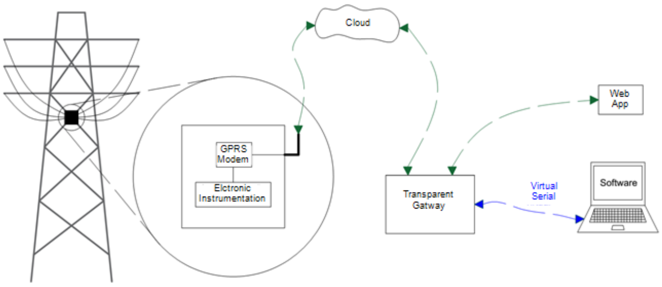
2.0 DEVELOPMENT

2.1 POWER INSULATORS LEAKAGE CURRENT MEASUREMENT SYSTEM (ILCM)

The entire insulator leakage current measurement system (ILCM) was designed so that its application in the field and live line could be facilitated, with the least degree of intervention in the power system and greater safety of the installation technical team. As the initial proposal provided for the installation for monitoring overhead TLs networks, the topology presented in Figure 1 was considered. This diagram shows the application topology of the ILCM system, composed of inductive and sectionalabled current sensors, electronic instrumentation with embedded system, communication by General Packet Services Radio (GPRS) protocol, web data server and data management software.

Leakage current data are periodically acquired, using as a method the acquisition of four periods of the industrial frequency of the current signal, where the instrumentation microcontroller performs the calculation of the current rms value and transmits the information of the six chains in a single package data to a remote web server through the GPRS protocol. The user uses a local terminal to communicate with a transparent gateway responsible for receiving data from the cloud.

Figure 1: ILCM System Block Diagram



2.2 CURRENT SENSORS

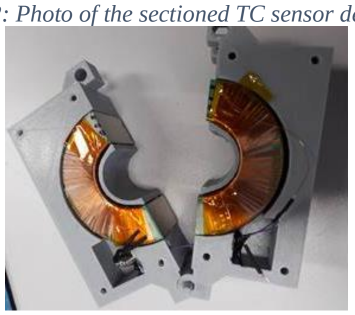
So that there is minimal intervention in the network and maximum safety of the installation technical team, six transducers were developed with current transformer (CT) topology with a sectional core for application on the grounded side of the insulators chain.

In this device, current from the insulator chain flows through the anchor pin in the tower and the CT will surround this element. As the CT core is surrounded by coils of conducting wire, the magnetic flux concatenated by these results in a potential at its terminals.

Due to the reduced amplitude of the current signal in the CT primary, the sensor cores are made of magnetic material with high relative magnetic permeability (μ_r), permalloy. This material is composed of an alloy of nickel, iron and molybdenum, in approximate proportions of 80%, 15% and 5% respectively. In this way it is possible to obtain parts with μ_r of up to 300,000.

For this project, six sensors were made with sectioned toroidal cores, as shown in Figure 2, which shows the structure of the developed CTs, showing the two halves of the magnetic core with winding of the turns.

Figure 2: Photo of the sectioned TC sensor developed



The coils were rolled evenly on both sides in order to minimize interference from external magnetic fields. n this topology, external fields show influence with reverse polarity in radially opposite turns. Each sensor is 110 mm long, 81 mm wide, 35 mm high and 23 mm internal diameter and its structure was made in a 3D printer with polymeric PLA material.

According to the theories of electromagnetism [10], the voltage induced at the terminals of a coil, formed by N turns, as a function of the current flowing in a central conductor to it, can be calculated according to equation (1), where the greatness are shown in Table 1.

$$V = \frac{N.\omega.\mu_0 \mu_r.A.I_{rms}}{2.\pi.D} \text{ [V]} \quad (1)$$

Table 1: Greatness used in equation 1

Symbol	Meaning	Unity
N	Number of turns	-
ω	Angular frequency	rad/s
μ_0	Magnetic permeability of vacuum	H/m
μ_r	Relative magnetic permeability	-
A	Core cross-sectional area	m^2
I_{rms}	Rms current of the center conductor	A
D	Average distance between center conductor and turns	m

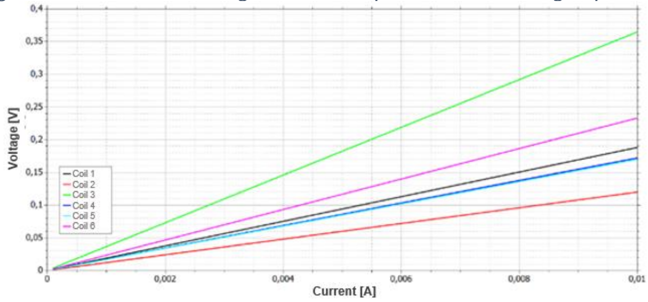
Using the average μ_r data presented by the supplier of magnetic cores, simulations were carried out to determine the number of turns necessary to obtain an adequate voltage signal for measurement and subsequent conditioning by the instrumentation. A total of 500 turns were obtained as an adequate value for this step. Applying 500 turns and inserting known signals, the relative magnetic permeability μ_r of each coil can be determined, as shown in Table 2.

Table 2: Relative permeabilities of permalloy cores

Core	Relative magnetic permeability [μ_r]
1	24.948
2	15.896
3	48.396
4	22.832
5	22.557
6	30.916

From equation 1, from the determination of μr and use of sensor design parameters, it was possible to simulate the voltage induced at the CT terminals (Figure 3) for the current range of interest, between 100 μA and 10 mA, considering 500 turns on each sensor. In this configuration, the core with lower permeability presents an induced voltage of 1.7 mV for the lower current limit.

Figure 3: CT induced voltage simulation for the current range of interest



2.3 ELECTRONIC INSTRUMENTATION

Due to the differential characteristic of the output signal of the CTs, the A/D converter of the microcontroller (ARM cortex M4) is configured to operate in this same topology, ensuring maximum common-mode noise rejection, present in the electric field coupling. Analog circuit stages coupled to the CTs inputs were also designed, whose purpose is to clip the signal at positive levels so that the AD converter operates properly [11].

At the input of the Cts, low-pass filters are also applied for frequencies above the 20th harmonic of 60 Hz, necessary so that only the industrial frequency signal is captured, eliminating high frequency components, resulting from discharges, which do not make up the current of main leakage and which can damage the equipment.

The instrumentation also has amplification circuits, suitable for differential measurement, precision multiplexers, communication system and decimation and filtering algorithms applied to the microcontroller firmware, where the latter element accumulates and transmits information in a data protocol developed specifically for this system.

The transmitted information contains a header with data referring to the identification of the source equipment (up to 255 devices), transmitted word size, temporal information, current rms values of the six CTs and error detection bytes.

2.4 WEB APP SOFTWARE

In order to allow the visualization and analysis of field and laboratory data in a scalable way on simultaneous devices (up to 255 devices), a web server was developed to receive and store data in the cloud using Java and Javascript languages with Node technologies .js, RabbitMQ and MySQL database.

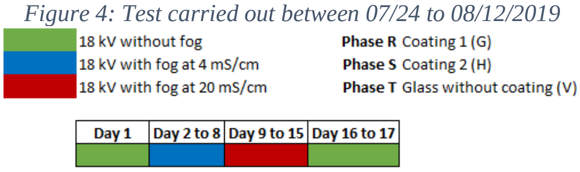
A web application (site) was also developed to visualize historical in real-time data using the Java language and Angular technology with Typescript, for conventional internet browsers.

2.5 SYSTEM APPLICATION IN LABORATORY

After the development and validation of this system [11], was possible to apply it to various laboratory and field conditions. After being installed in an experimental arrangement of an artificial pollution chamber, tests were carried out to verify the behavior of different coatings on glass insulators.

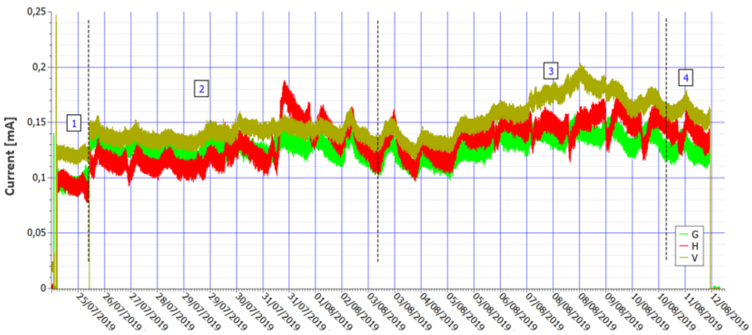
A first laboratory test was realized between July 24th and August 12th, 2019 in a group of uncoated glass insulators and another with RTV-SIR type coating. In phase R, the insulator with coating 1 (G) was installed, in phase S the insulator with coating 2 (H) and in phase T the uncovered glass insulator (V). This test was carried out with two discs in each phase and application of 18 kV. The variation in the conductivity of the applied salt spray is illustrated in Figure 4.

Figure 4: Test carried out between 07/24 to 08/12/2019



The points on the graph in Figure 5 numerically marked from 1 to 4 correspond to the steps of application of the potential without mist and with mist of 4 mS / cm and 20 mS / cm.

Figure 5: Leakage current of the insulators under test from 07/24 to 08/12/2019.

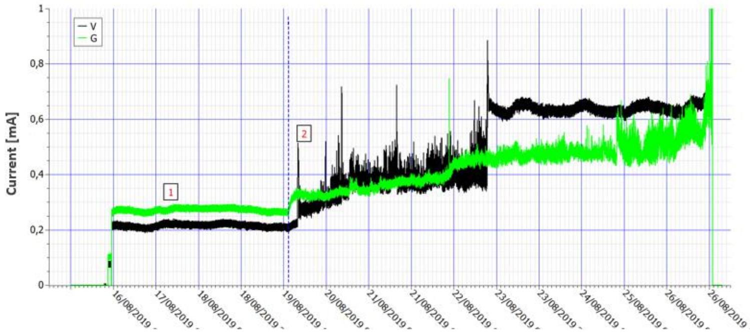


The fog conductivity values were obtained according to ABNT NBR 10621 and ABNT IEC/TS 60815-1 and the values seek to simulate an environment with a LIGHT (4 mS/cm) and MEDIUM (20 mS/cm) pollution severity level.

It can be observed that the glass insulator (yellow curve) has a tendency to increase the leakage current in the period, especially at point 3. Insulators with coating in RTV-SIR, on the other hand, seem to have a tendency to a constant mean value. Points 1 and 4 on the graph are the moments when there is application of potential without mist and moments 2 and 3 correspond to application of mist at 4 mS/cm and 20 mS/cm, respectively.

From August 16 to 26, 2019, a new test was carried out in the fog/artificial pollution chamber. In this test, lasting 11 days, a fog with a conductivity of 4 mS/cm was used. In this, a voltage of 18 kV was applied in a disk unit in each phase, being: phase R - coating 1 (G), phase S - coating 2 (H) and phase T - glass (V). The data from this test are shown in Figure 6 and 7, where Figure 6 shows the comparison of the leakage current of the coating 1 (G) and glass (V) insulators. Regions 1 and 2 of the graph correspond, respectively, to the application of potential without mist and application of potential with mist with a conductivity of 4 mS/cm.

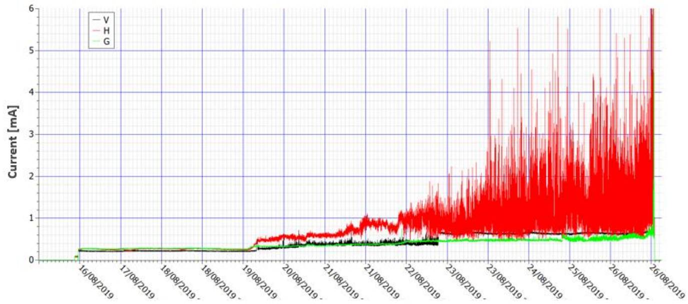
Figure 6: Test leakage current data for insulators from 16 to 08/26/2019 coating 1 (G) and glass (V).



In Figure 6 it can be seen that initially, without the application of fog, the leakage current intensity of the covered insulator with coating (G) is higher than the uncovered insulator (V). However, after a short period of fog application, this condition is changed, that is, the glass insulator starts to present a higher leakage current.

For the purpose of comparing the two insulators shown in Figure 6 with the insulator covered with coating 2 (H) the graph shown in Figure 7 was drawn up, where it can be seen that in all situations the insulator covered with coating 2 (H) maintained the intensity of leakage current greater than the glass insulator (V), resulting in current intensity signals close to the superior resolution of the equipment (10 mA), resulting from discharges on the surface of the material.

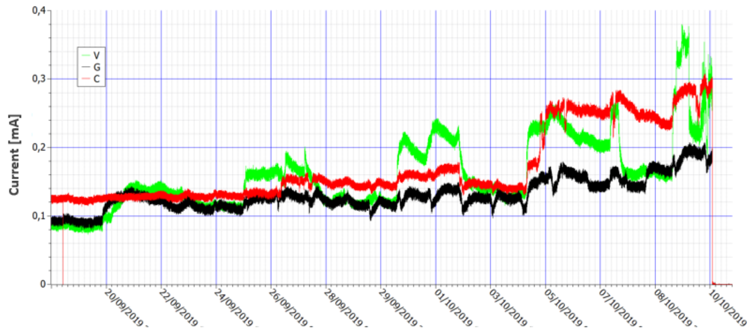
Figure 7: Leakage current data of insulators under test from 16 to 08/26/2019 coating 1 (G), coating 2 (H) and glass (V).



It was not possible to perform the test with a disk unit in each phase with fog conductivity at 20 mS/cm (simulation of average pollution), as the protection of the chamber's electrical system disarmed for the resulting leakage current intensity, possibly from the covered insulator with coating 2 (H).

Between 9/18 to 10/10/2019 an alternating test of tension application under saline mist was carried out, lasting 23 days. This test was designed to maintain in each phase two disks with the same coating technology, that is, 2 disks in series mounted on each phase, as follows: R phase - coating 1 (G), S phase - coating 2 (C) and T phase - glass (V). During the test period, the mist was maintained at 20 mS/cm, where in alternating periods of 2 days the conditions of application of voltage of 18 kV and absence of voltage were maintained. From this test, the data presented in Figure 8 were acquired.

Figure 8: Leakage current data of the insulators under test from 09/18 to 10/10/2019.



It is verified that after the voltage-free period, the leakage current levels did not return to the intensity of the last applied voltage period. It is suggested that this is due to the accumulation of material on the surface of the insulator. It can be seen that the glass insulator was the one with the highest leakage current values. The insulator with coating 1 (G) showed the lowest leakage current values, with practically constant behaviour throughout the test period (values between 100 and 200µA).

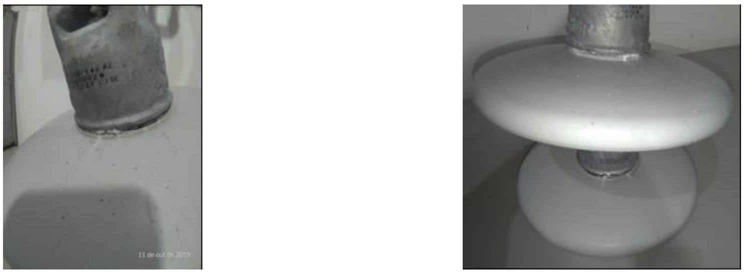
After completion of the tests, the insulators were photographed to assess the surface condition. The images obtained are shown in Figure 9, 10 and 11. In Figure 9a it can be seen that there was a formation of a salt deposition path on the surface of the upper insulator, which was sufficient to increase the leakage current in the set. This deposition was not observed in the lower insulator (Figure 9b).

Figure 9: Glass insulator after testing carried out between 9/18 to 10/10/2019.

a) b)

In Figure 10a, the presence of traces of formation of a salt deposition path can be noticed, as well as small particulate spots on the surface of the upper insulator. This was not observed in the lower insulator (Figure 10b). These traces and salt dots did not form a continuous path, corroborating the more regular nature of the observed current.

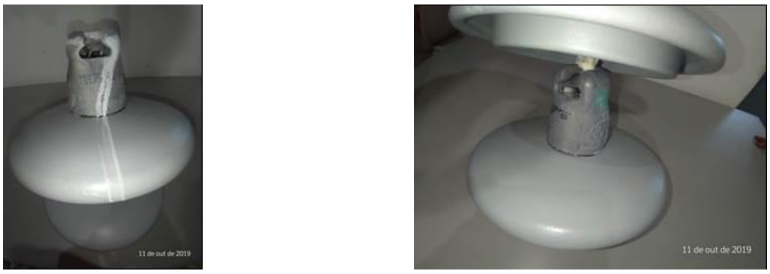
Figure 10: Covered glass insulator with coating 1 (G) after testing carried out between 9/18 to 10/10/2019.



a) b)

In Figure 11a, it can be seen that there was the formation of a salt path deposited on the surface of the upper insulator, sufficient to increase the leakage current observed in the test. In the lower insulator (Figure 11b) it is not observed the presence of traces or points of salt accumulation.

Figure 11: Covered glass insulator with coating 2 (C) after testing carried out between 9/18 to 10/10/2019.



a) b)

It is also worth noting that the coated insulator (G) is a factory painted material and the coated insulator (C) is a material painted in Lactec with an industrial spray gun, this illustrates the effect of the quality of the paint on the final product.

2.6 SYSTEM APPLICATION IN FIELD

On August 14, 2019, the installation activity of the second unit of equipment in the field was carried out. The selected location was Tower 6 of the 230 kV Bateias – Campo Comprido TL located in the city of Campo Largo, metropolitan region of Curitiba PR - Brazil, where the insulators that received the sensors were the 3 of Circuit 1. In this circuit, the chains of suspension insulators received the anchoring pin used in the development of the project and all 14 glass insulators in the chain were replaced by new insulators.

The tower selected for the application of the ILCM is a 230 kV LT with a height of 40 meters and a distance between phases of 5.5 meters. In this, the sensors are connected to the instrumentation, which is inserted in a control box, through shielded electrical cables.

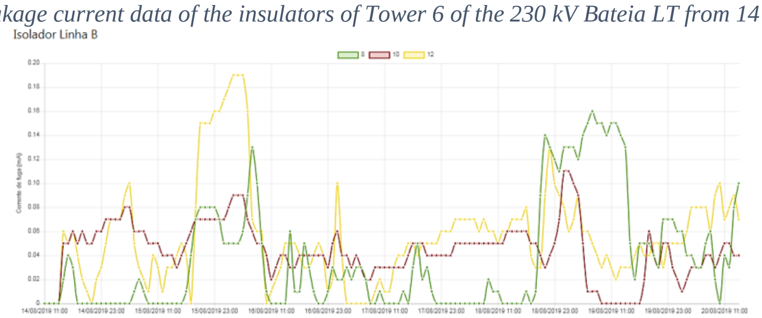
During the installation stage in the tower, the equipment proved to be easy to handle and install in the field, even in the case of live line activity. Figure 12shows the the elements of the ILCM system installed in the 230 kV TL tower.

Figure 12: Installation of ILCM system in TL tower. a) sensor in the insulator chain, b) control box with electronic instrumentation and c) solar panel

a) b) c)

Figure 13 shows the data from the field sensors, collected between the 14th and 20th of August, 2019. The lower chain is represented by sensor 8 (green line), the central chain is represented by sensor 12 (yellow line) and the upper chain is represented by sensor 10 (red line).

Figure 13: Leakage current data of the insulators of Tower 6 of the 230 kV Bateia LT from 14 to 08/20/2019.



This figure is collected directly from the screen of the developed application, for this reason the legend are presented in Portuguese. It is verified, through these data, that the leakage current in the glass insulators in the field presents an irregular behavior, whose variation is related to the environmental conditions (humidity and temperature) of the region where it was installed. On the other hand, the order of magnitude of the current measured is similar to values already observed in the laboratory (about 200 µA). There are times when the leakage current reaches the lower limit of the instrumentation scale, less than 1 µA, and for this reason the data is shown as zero.

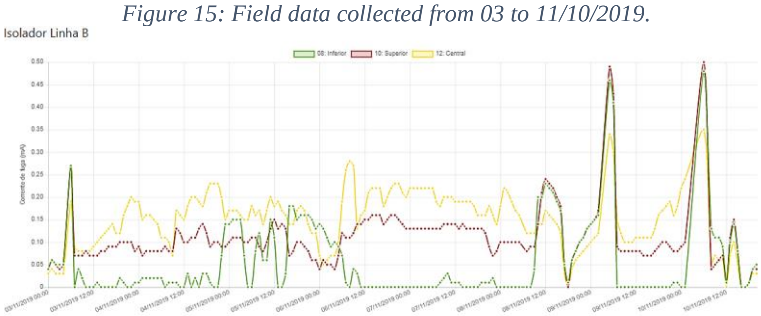
The data in Figure 14 were collected from October 17th to 21st, 2019.

Figure 14: Field data collected from 10/17/2019.

It can be noted that in the periods from 10:00 pm to 10:00 am of the following day (on average) the leakage current of the insulators increases and reaches values of up to 500 µA , probably caused by the elevation of the local humidity. This fact is also observed on the dates of October 19th and 20th, in the period of 4 pm, when there was rainfall in Curitiba and in the place where the equipment was installed. In periods of lower humidity, the leakage current values are reduced and reach values below the equipment's resolution.

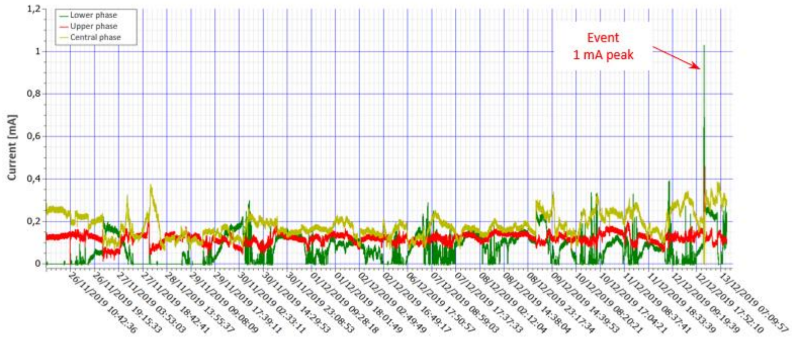
The continuous monitoring of the leakage current in the insulators of the 230 kV Bateias – Campo Comprido transmission line shows that the two upper phases present higher values for this magnitude, while the lower phase remains with a current close to zero. However, observing the scale of the graph in Figure 15, it can be seen that the amplitude in the three phases is in a few hundred microamps, which, according to laboratory tests, indicates that the insulators are in good clean condition.

Figure 15: Field data collected from 03 to 11/10/2019.



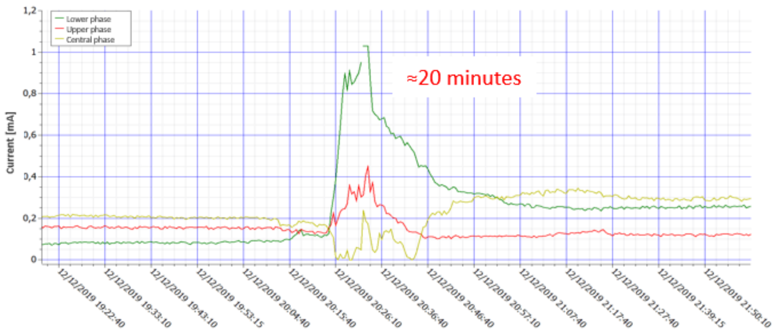
Uninterrupted data were collected from November 26th to December 13th, 2019. These data are shown in Figure 16.

Figure 16: Field leakage current data from 11/26 to 12/13/2019



A sharp increase in leakage current (Event) can be observed on December 12, where this magnitude went from constant levels less than 400 uA to greater than 1 mA. Expanding the graph in Figure 16, one can accurately observe in Figure 17.

Figure 17: Field leakage current data on 12/12/2019



The duration of the event, about 20 minutes at night, where the chain of insulators closest to the ground adds the current by 10 times the stability value. The other chains showed interferences with a similar characteristic, with a tripled value in the upper chain and a reduction in the central chain.

3.0 CONCLUSIONS

The development of equipment, consisting of electronic instrumentation that makes use of CT-type current sensors with magnetic cores of high relative permeability, combined with analog filtering and amplification circuits and digital noise reduction techniques, with measurement, was proven and validated capable of collecting leakage current data of interest in the order of noise, even immersed in a region of intense electromagnetic fields, as proven in the application in 230 kV LT tower.

The equivalent resolution obtained by the ILCM system for the lowest sensitivity CT was 471 nA at industrial frequency, although the data presentation is in 1 µA steps, making the ILCM system suitable for measuring current signals in the range of 100 uA to 10 mA, as presented in the literature as range of interest for analysis of pollution deposition/surface degradation of high voltage insulators.

The use of current transformers with a sectionable core allows installation in the field without the need for a supply interruption, as the chain does not need to be interrupted.

The system is expandable, that is, up to 255 devices can be inserted into the system so that the leakage current data is stored in the server.

It was observed in the laboratory that coating insulators with hydrophobic coatings does not necessarily lead to performance improvements. In all tests performed, the RTV-type silicone rubber cover keeps the leakage current stable at a level lower than that of glass under the same conditions. Thus, insulators with this coverage show similar behavior in dry environments or with the presence of mist, unlike those found. On the other hand, insulators with traditional hydrophobic coatings initially present a lower leakage current than those discovered.

In relation to field equipment, it appears that the web application allocated in the cloud behaves properly as a supervisory system that is easy to interpret and accessible by any browser on any fixed or mobile device, favoring monitoring by several technical teams simultaneously, allowing verification and analysis of current rise occurrences in short periods of time, data that are easily made up by the temporal average if they were not acquired and stored.

Although the field system has been applied to TL insulators, it is possible to expand its application to meet DLs in the different types of insulators used. The expansion of application of this system for fault detection is noteworthy, so that it signals the location that is still energized and not energized, informing the utility's monitoring center.

Finally, it is concluded that in addition to laboratory analyses, with greater appreciation for the safety of data acquisition, this system can integrate smart grids in the electricity sector, providing greater reliability in the use of its assets.

4.0 ACKNOWLEDGMENTS

The authors of this article are grateful to the institutions Companhia Paranaense de Eletricidade - COPEL Geração e Transmissão and ANEEL (National Electric Energy Agency), which, through the research project PD 6491-0351/2014, made this study feasible.

BIBLIOGRAPHY

[1] GHOSH, R., CHATTERJEE, B., CHAKRAVORTI, S. A Method for Unambiguous Identification of On-Field Recorded Insulator Leakage Current Waveforms Portraying Electrical Activity on the Surface. IEEE Transactions on Dielectric and Electrical Insulation. Vol. 23. No 1. 2016.

[2] GORUR, R. S. de la O, A. Flashover of Contaminated Nonceramic Outdoor Insulators in a Wet Atmosphere. IEEE Transactions on Dielectric and Electrical Insulation. Vol. 5. No 6. 1998.

[3] ZHOU, J., c, Y., CHENG, T., ZHAO H. Research on Routing Algorithm for On-line Monitoring of leakage Current of Insulators. IEEE 2nd Advanced Information Technology, Electronic and Automation Control Conference. 2017.

[4] ABEYSEKARA, A. H. A. D., KUMARA, J. R. S. S., FERNANDO, M.A.R.M., EAKANAYAKE, M.P.B., GODALIYADDA, G.M.R.I., WIJAYAKULASOORIYA, J.V. Remote Leakage Current Detector for Identification Insulators Discharges. IEEE Transactions on Dielectric and Electrical Insulation. Vol. 24. No 4. 2017.

[5] RCHMAWATI, FAUZIAH, D., ALFIADI, H., SUWARNO. Leakage Current Characteristics Study on Electrical Equivalent Circuit of Field-Aged RTV Silicone Rubber Coated and Noncoated Insulators in a Coastal Area. International Conference on High Voltage Engineering and Power System. Bali, Indonesia 2017.

[6] RAMIREZ, I., HERNÁNDEZ , R., MONTOYA, G. Measurement of Leakage Current for Monitoring the Performance of Outdoor Insulator in Polluted Environments. IEEE Electrical Insulation Magazine. Vol. 28. Issue 4. 2012

[7] MELIK, C., DONG, Z., ZHOU, L., ZIQING, Y. Insulator Leakage Current Monitoring, Its Application and Advantages. 6th China International Conference on Electricity Distribution. Shenzhen 2014

[8] PYLARINOS, D., SIDERAKIS, K., PYRGIOTI, E. Measuring and analyzing leakage current for outdoor insulators and specimens, Advanced Materials Sci., Vol. 29, No. 1, pp. 31-53, 2011.

[9] RCHMAWATI, FAUZIAH, D., ALFIADI, H., SUWARNO. Leakage Current Characteristics Study on Electrical Equivalent Circuit of Field-Aged RTV Silicone Rubber Coated and Noncoated Insulators in a Coastal Area. International Conference on High Voltage Engineering and Power System. Bali, Indonesia 2017.

[10] HAYT JR., W. H., BUCK, J. A. Eletromagnetismo. Editora AMGH. Ed 8. 2013

[11] USSUNA, D.A., CARVALHO, R.V., SWINKA-FILHO, V., FRESHI, E.F., FARIAS, W.C., TONETTI, M., SILVA, G.C. SISTEMA DE MEDIÇÃO EM TEMPO REAL APLICADO À ANÁLISE DE CORRENTE DE FUGA DE ISOLADORES DE LT 230 KV. XIII Simpósio de Automação do Sistema Elétrico SIMPASE. Recife 2019.