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Adding Intelligence to Ceramic Insulators

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1. Abstract

The Digitalisation of a substation contains several challenges for data capturing and transmission. Fiber Optical technology is one of the solutions as it is EMI/RFI immune and has achieved a good level of maturity, which has pushed the costs down. Furthermore, the optical sensor technology does not need a power source at the measuring point; the light source can be hundreds of meters away and outside the substation itself. Installing a Fiber Optic Cable at the substation is another challenge, as it should go through the insulators.

This article will explain the method of manufacturing a Fiber Optic Hole in a Ceramic insulator using existing applications, and explore potential future applications in monitoring forces, movements and vibrations of ceramic insulators as part of a Digital Substation.

2. Opto-Electronical Technologies

Rayleigh, Brillouin and Raman scatterings in fibres result from the interaction of photons with local material characteristic features like density, temperature and strain. For example, an acoustic/mechanical wave generates a dynamic density variation; such a variation may be affected by local temperature, strain, vibration and birefringence. By detecting changes in the amplitude, frequency and phase of light scattered along a fiber, one can realize a distributed fiber sensor for measuring localized temperature, strain, vibration and birefringence over lengths ranging from meters to one hundred kilometres. Such a measurement can be made in the time domain or frequency domain to resolve location information. With coherent detection of the scattered light one can observe changes in birefringence and beat length for fibres and devices. These distributed sensors can be used for disaster prevention in the civil structural monitoring of pipelines, bridges, dams and railroads. A sensor with centimetre spatial resolution and high precision measurement of temperature, strain, vibration and birefringence have find applications in aerospace smart structures, material processing, and the characterization of optical materials and devices. [1]

The conventional sensor piezoelectric sensors is constrained under high temperatures; its crystalline nature dictates a well-determined Curie temperature, as a limit and proves to be inadequate when measuring static quantities due to charge leakage. These limitations make piezoelectric sensors an unsatisfactory solution in which reliability, hardiness and ease of incorporation are a requirement: for example, situations like sensor embedding in aerospace wing components, in large induction motors or on High Voltage power lines. [2]

With the development of opto-electronic technologies and the increasing industrial requirements, optical fiber sensors have now been widely accepted and have achieved a technical maturity. The advantages of opto-electronic sensors are significant, especially for those applications in harsh environment, such as oil field service, civil engineering, navigation, high voltage and monitoring in oceans. The opto-electronic sensors are immune to Electromagnetic Interference and Radio Frequency Interference (EMI/RFI), are small size, and easily integrated with networks. They have other advantages as well, including extremely high sensitivity at low frequencies, low harmonics distortion (THD), high signal-to-noise ratio (SNR), high signal quality, long term reliability and stability and very low losses on long optical data connections.

Today, standard industrial sensors like Optical Microphones, Optical Temperature Sensors, Optical Accelerometers and Vibrometers are available from multiple manufacturers. Among the practical applications for Optical Sensors, the most common uses include Fiber Optical Geophones for ocean seismicity measurement, Raman Optical Time Domain Reflectometer (ROTDR) for down well distributed temperature sensing, and Optical Vibration sensing systems for petroleum pipelines protections. The need for fiber sensors has increased rapidly, and the market is growing quickly. In this fast-developing market, manufacturing volumes have increased exponentially, leading to significant cost reductions.

The Fiber Optic Current Sensor (FOCS) is already in use in High Voltage technology applications, and PPC has been delivering Fiber Optic Post Insulators for over 20 years. The FOCS uses the Faraday effect, which causes polarization of linearly polarized light to rotate at the presence of a magnetic field, when propagating in a material exhibiting the Faraday effect. [3]

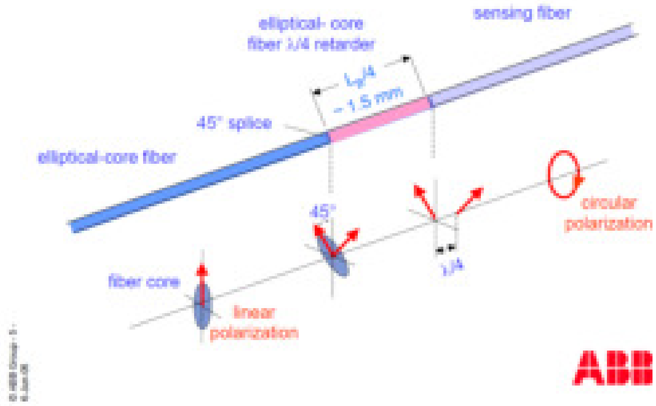

Fig. 1 The Faraday effect on FOCS [4]

The FOCS and related technologies have been widely studied, and there is with multiple articles available, so this paper will not delve deeper into this Opto-Electrical application.

3. Creating Fiber Optic Hole in a Ceramic Insulator

The technical challenge of using the Fiber-Optic technology with ceramic insulators is how to manufacture the insulator with a 15 mm and straight 3 m long hole. C-130 is extremely hard material, which requires special drilling heads. To keep the hole straight through the entire length is another technical challenge. This makes the drilling rather time consuming and expensive when conventional drilling technologies are used.

Manufacturing such a precise small hole with the conventional plastic extrusion process, used for ceramic insulator production, would not be possible. PPC Industrial engineers have found a smarter way to create the holes then drilling or extrusion.

PPC is able to take advantage of years of its accumulated knowledge of the Cold Isostatic Pressing (CIP) process and its possibilities. Fine and carefully controlled granulate, with a very specific grain-size distribution is prepared first. A cylinder is filled with the granulate, which is then pressed to over 1000 bar pressure which results a solid blank for shaping and firing. At this stage of the process an insert is added to the cylinder, which remains in place during the compression phase. The insert is removed after the compression, and before turning. Fig 2 shows the ready turned blank with a Fiber Optic hole, ready for glazing and firing.

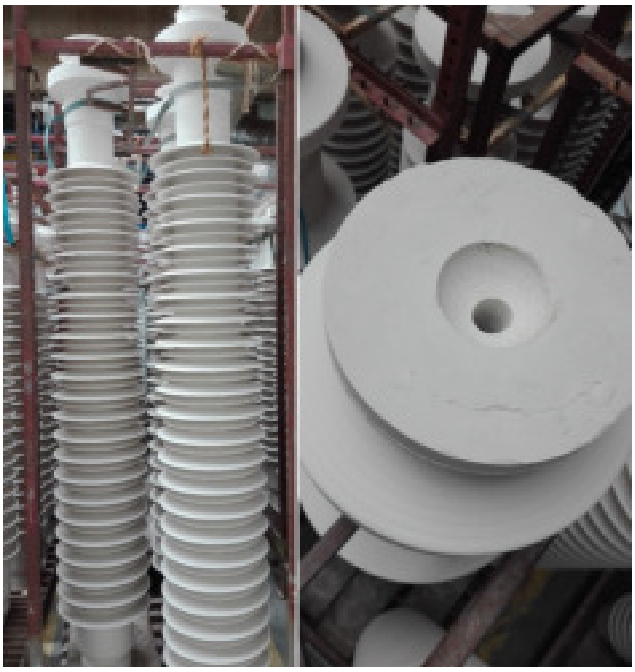

Fig 2. Fiber Optic Hole Post insulator ready for glazing and firing.

Once the Insulator has been fired, the production continues using the conventional insulator manufacturing process: cutting, grinding, assembly and testing. Fig 3 shows the fired C30-850 post insulator with a perfectly straight 20 mm hole on the central axis. The fittings must be pre-drilled, and the hole and threads must be protected for the cementing process. Fig 4 shows the completely assembled insulators.

Fig 3: Fiber Optic Hole Post Insulator after firing and cutting.

Fig 4: Assembled C30-850 Fiber Optic Post Insulator ready for testing.

The Fiber Optic hole is on the neutral axis and does not affect the mechanical strength of the insulator. To confirm this statement samples of C30-850 Post insulators were manufactured for Benchmarking bending tests Fiber Optic holes. The tests were performed at PPC Plant CAB in Slovakia. Fig 5 shows bending test set-up.

Fig 5: Bending test at PPC Insulators CAB.

The results are on the Table 1.

Sample Number	C30-850 Standard Post	C30-850 Fiber Optic Post
Sample 1	41,03 kN	41,63 kN
Sample 2	40,48 kN	43,44 kN
Sample 3	38,90 kN	46,50 kN
Sample 4	40,59 kN	40,25 kN
Sample 5	40,48 kN	42,30 kN
Sample 6	40,70 kN	---
Average	40,36 kN	42,82 kN
Standard Deviation	0,680	2,108

Table 1: Breaking force of C30-850 Post Insulators, 30 kN is the nominal strength.

The bending tests results indicate that the mechanical strength of the Fiber Optic Post Insulator is not affected the hole in the neutral axis. Further, this destructive test allowed us to observe whether the breaking mechanism was identical to that which occurred with standard posts. All the samples broke on the 2nd or 3 shed at the bottom, where the cantilever forces are greatest. The breakage surface was identical to the breakage surface of the standard post insulator, so it can be concluded that the presence of the hole does not affect the strength, breakage mechanism, or crack propagation of the ceramic.

Fig 6: The broken Fiber Optic Post Insulator. The Fiber Optic Hole is not affecting the breakage mechanism.

4. Sensing inside of the porcelain

A post insulator manufactured with Fiber Optic Hole allows a Fiber Optic Sensor to be placed inside the insulator, rather than simply drawing the fiber inside.

Stresses and strains in any solid material may be resolved into six components: three compressive or dilatative, and three shears. These stresses cause acoustic waves in the materials, which vary considerably with the microstructure and elasticity of the material. The frequency and amplitude of the acoustic waves vary as well, depending on the source of the stress itself. These waves can be recorded using microphones, and the data analysed. This technology is well known and widely used in the preventive maintenance and monitoring of rotative machines (turbines, etc). [5]

The same principles could be used to monitor a ceramic insulator in a substation. Stresses may be caused by wind, vibrations from the overhead line, external impact or movements of the switch when an insulator is used to transfer force as a torsion rod. Data collected during these events would provide valuable information necessary to understand the physical shape and functioning of an insulator, or of the system in which the insulator is a component. This information could then be added to the monitoring system the substation.

A short feasibility test was organised jointly between the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, and PPC Insulators CAB. [6]

An Insulator was placed vertically into a bending machine at the CAB plant test facility. A microphone was placed into a cable hole, and the lower end of the hole was filled with foam. The upper end of the cable hole was filled with foam as well, to isolate the microphone from environmental factors outside the insulator. An accelerometer was then glued to the surface of the insulator using epoxy glue. Figs. 7 and 8 show the test set-up.

Insulator under test was loaded 21 times with different force and different bending rates. The test programme with accelerometer and microphone is presented in the Table 2.

Fig 7: Test Set up with a microphone inside the Fiber Optic Hole and Accelerometer glued on the shed.

Fig 8: Test Set up on the CAB Bending machine.

Bending Load/ Speed	50 %	95 %	100 %	105%
10 mm/min	2 tests	10 tests		
3 mm/min		3 tests	3 tests	3 tests

Table 2: Test programme with Microphone and Accelerometer

The first goal was to understand whether the acoustic waves are dependent on the internal stress of the insulator material. During the first test, the insulator was mechanically excited by tapping it with a metal rod. The direction of the tapping was perpendicular to the insulator axis. The measurement began with no force on the insulator. Responses to five taps approximately one second apart were recorded. Next, the insulator was loaded to 50% and again five tap responses were recorded. This scenario was repeated for a 95% load. Responses to taps were individually normalized to have the same amplitude. Fig. 9 shows three normalized impulse responses at different loads of 5 %, 50 % and 95 %.

Thus, it can be concluded that the stress level of the ceramic is not affecting the acoustics signals.

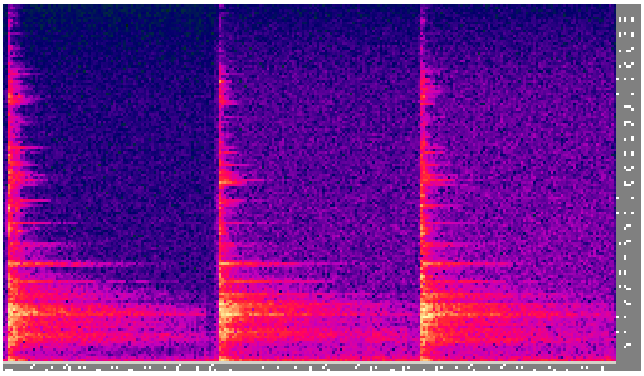

Fig. 9: Spectrograms of three responses captured at different loads, 0%, 50% and 95%.

Fig. 10 shows measurement sets shows two groups of resonant modes, the first group is approximately 3 kHz, and second group is single resonant mode at 18.85 kHz.

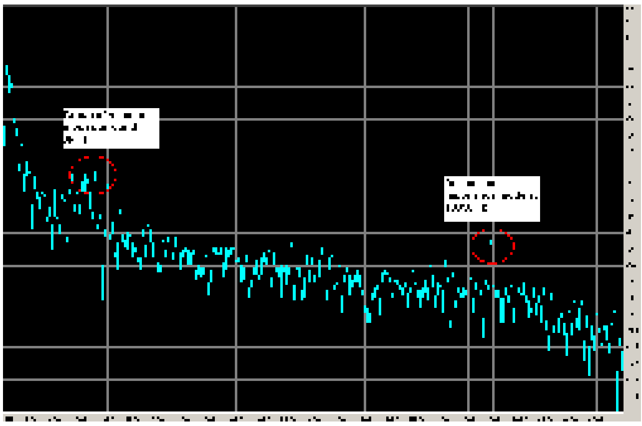

Fig. 10: The example of spectrum of resonant modes at 15kN load. Window size: 2048 samples, windowing type: Blackman-Harris.

The resonant modes at the load values, when compared, indicate the resonant modes did not have a direct correlation with load, and cannot be directly used to determine load acting on the insulator.

A Neural network can find connections between events in processed signals that are normally hidden from human sight or are too complicated to be processed by a human. Proper training of the neural network is essential for its correct operation. The quality of a training process is strongly dependent on the sample size. The sample size of 21 measurements is insufficient to train a neural network. The required sample size should be at least 100 times larger, and it would still not guarantee the success of this approach.

Accelerometers can be used to measure vibrations, direction and magnitude of acceleration and direction of vector of gravitation acceleration. Since the insulator was fixed to the test machine, it was possible to measure only vibrations and gravity acceleration. The measured vibration data was very similar to the acoustic data. The most valuable data came from measuring the angle of gravitational acceleration. After filtration and processing of the data, it was possible to calculate deflection of bend of the insulator and correlate it to the bending load. Fig. 11 shows the processed measurement data as bending force over time.

It was observed that the bending was not 100 % reversible, and the insulator did not return to its original position. In this case, the testing loads were extremes, and it is improbable that any insulators permanently operate at 95 % the nominal strength. A different insulator will have different ratio between bending force and deflection, thus measuring bending ratio for each individual insulator would be required to confirm a systematic correlation.

The feasibility test also suggests that any system using ceramic insulators with optical sensors would require a calibration process after installation at a substation.

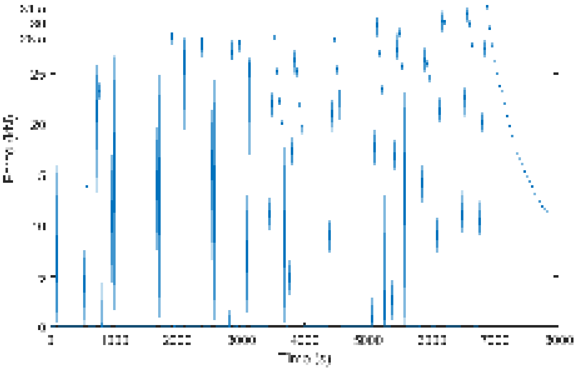

Fig. 11 Bending force over time.

5. Conclusions

The manufacturing of a Fiber Optic Post insulators is possible in an industrial and cost-effective way using the Isostatic manufacturing technology. The Fiber Optic hole is on the neutral axis and is not affecting the mechanical performances of the insulator.

It is possible to measure acoustic waves and vibrations inside a ceramic post insulator. The stress level of the ceramic does not affect the acoustic signals frequency or propagation in the material itself. The measurements made with an accelerometer showed a good correlation to the real measured deflection, which also theoretically allows an indirect measurement of the force.

It was not possible to detect direct correlation between the applied force and measured acoustics wave; the number of measurements weren't enough for proper training of a neural network to accomplish a deeper analysis.

The Fiber Optic hole allows the addition of sensing and data gathering capabilities to ceramic insulators. The data collected can be used, once filtered and analysed, for substation monitoring. It is the first step toward an intelligent Insulator, which can sense its environment and provide important system data for management of the substation.

Further work is needed to confirm the repeatability of the measured data and determine a correlation between the load and acoustic wave.

6. References

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