ON-LINE, EARLY WARNING, REMOTE PARTIAL DISCHARGE MONITOR FOR HIGH VOLTAGE POWER TRANSFORMERS.

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INTRODUCTION

Partial discharges are a reliable precursor of electrical breakdown of insulation inside a transformer and so serve as an early warning if they can be reliably detected amongst the plethora of electrical noise in a substation. This new on-line continuous monitoring system detects partial discharges by using both the radio frequency and ultrasonic signatures produced by the partial discharges which are statistically sampled. Following signal processing a four level alarm is provided locally at the substation and remotely by modem communication. The system has been fitted on new and retrofitted on old transformers in Australia. Early warning results in savings in maintenance and replacement costs, extension of the lifetime of high voltage transformers, improved safety and avoidance of environmental pollution

DETECTION OF PARTIAL DISCHARGE

This monitoring system works by detecting both the ultrasonic and radio frequency signals that are generated by partial discharges. The special ultrasonic and radio frequency detectors are fitted so they are immersed in the mineral oil inside the transformer and flush with the inside surface of the wall or roof of the transformer. Critical for the functional operation of this system the radio frequency and ultrasonic signals travel at different speeds from the partial discharge source and the system measures the time interval between the arrival of the radio frequency and ultrasonic pulses. Each pair of ultrasonic and radio frequency detectors are housed as part of a sensing "head" which is installed either through the wall of the transformer or through an inspection plate. The introduction of these transducers into the transformer does not interfere with the performance of the transformer. The transducers inside the transformer immersed in mineral oil are supported by a lead-through plate with an O ring seal. At the other side of this plate, the transducers are electrically coupled to special analogue electronic processors which are housed in a metal box. Each sensing "head" consists therefore of a pair of transducers (ultrasonic and radio frequency), a sealed lead - through plate, an analogue electronic processor all covered by a metal box. An advantage of having the transducers inside the transformer and the electronics inside a box is that they are shielded from noisy signals from other parts of the substation.

SPECIAL DETECTORS

Ultrasonic Transducers

These transducers have to be very sensitive, matched acoustically to the mineral oil, have short ring down time and be capable of surviving in hot corrosive mineral oil up to 120°C for several years. There are no ultrasonic transducers available commercially which meet this specification since conventional ultrasonic transducers do not survive these demanding conditions. A short ring down time is essential to maximise the number of ultrasonic pulses detected.

Special composite transducers have had to be developed in-house specifically for this application. Acoustic impedance is the density times the velocity in the material through which the ultrasonic wave is travelling. The acoustic impedance of the receiver should be as close as possible to the acoustic impedance of the mineral oil so as to minimise the reflection. One can have a very sensitive detector but if the acoustic impedance of the transducer and the medium it is in contact with are widely different there will be very little acoustic energy to detect since most of it will be reflected. The use of piezoelectric ceramic in epoxy increases the electromechanical coupling k and the piezoelectric sensitivity parameters d_h and g_h. Composite structures have also lower acoustic impedance closer to that of the oil. The ring down time is reduced by the damping properties of the epoxy but in our design this was further reduced by use of tungsten loaded backing on the transducer. These special transducers have been found to meet all the requirements and survive for more than three years in mineral oil up to temperatures of 140°C without loss of the original high values of k, d_h and g_h . The encapsulation using the special 1-3 composite configuration ensured a rugged, chemically resistant transducer which survives the demanding conditions and also the low frequency magnetostrictive vibrations propagated through the transformer. It was also critical that the mechanical coupling of the transducer into the lead through plate should be reliable. Low frequency vibrational tests up to 100g over several hundreds of hours showed the method of mechanical and electrical connection to be reliable.

When ultrasonic transducers are used on the outside of the transformer wall (as in fault location) there is severe acoustic mismatch and loss of acoustic energy. This is due to reflection at the inside wall of the transformer and at the interface between the transducer and the outer wall of the transformer inspite of using special couplants. Some of the energy goes as shear waves in the transformer wall.

These composite oil immersion transducers are much more sensitive than commercially available transducers. They also have low lateral coupling coefficients so that they are not affected by false signals due to shear waves which are generated in the walls of the transformer. These are generated when the ultrasonic longitudinal waves generated by mechanical vibrations impinge on the wall of the transformer at angles other than normal. This low lateral coupling improves selectivity since it causes the transducer to ignore spurious ultrasonic waves which bounce around between the inside of the wall and the laminated cores. These composite transducers have low electrical impedance (about 5 kΩ). The thickness resonance frequency was selected following Fourier power spectrum analysis of ultrasonic responses from numerous partial discharges produced artificially.

Radio frequency transducers

The radiated electrical field disturbance from a partial discharge is an impulse lasting only a few nanoseconds and is rich in high frequency components. To detect this radio frequency pulse a variety of antenna configurations were tried including coils and solenoids wound on ferrite cores. All responded to some degree but the most suitable geometry was a brass annular ring which surrounded the ultrasonic transducer so it was also flush with the inside wall of the transformer. The brass annular ring forms a capacitor to ground The electrical field disturbance excites a resonant circuit formed by the capacitive antenna to ground and the self inductance of the connected leads. This resonant high frequency can be adjusted between 10 MHz and 100 MHz by adding inductors in parallel. (Unsworth et al [1]). The frequency selected was based on Fourier power analysis of a electrical noise spectra from transformers in which there were known partial discharges.

Installation of the Heads

The number and placement of the detector heads depends on the transformer size and design. In general, the heads are placed where possible with an unobstructed view of the windings and in particular a view of the high voltage windings.

Analogue signal processing

All electronic components must be military specification standard since the analogue processors are housed in the head mounted on the transformer as close as possible to the transducers to minimise noise pick up. Transformers in Australia can get up to 120°C when heavily loaded and subjected to the hot sun.

The ultrasonic processing channel consists of an ultrasonic pre-amplifier, a 125 kHz high pass filter, a precision rectifier, a 1 kHz low pass filter, an amplifier and buffer as shown schematically in Figure1.

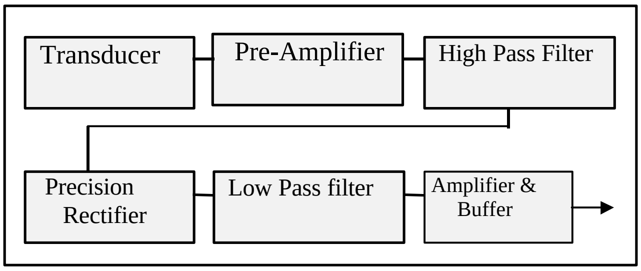

Figure 1 Ultrasonic Processor

The radio frequency processing channel consists of a radio frequency preamplifier operating in the range 1 to 70 MHz, a radio frequency precision rectifier, a 1 MHz low pass filter, a high speed comparator and a monoshot. This is illustrated in Figure 2.

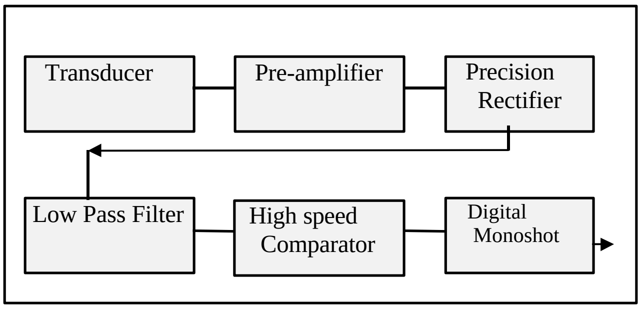

Figure 2 Radio Frequency Processor

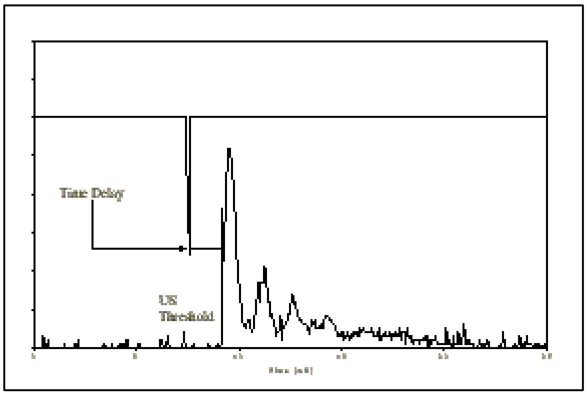

Figure 3 Processed Analogue Signal

Figure 3 illustrates actual recorded and processed radio frequency and ultrasonic pulses from a partial discharge. Also shown is the time delay between the two signals which depends upon the distance from the partial discharge source to the detectors and the material in the path.

Microprocessor

The analogue to digital (A/D) conversion takes place at 16 kHz in 100 mS blocks and processing takes place over 2 seconds and is then repeated.

The C++ program on the microprocessor calculates the ultrasonic amplitude, ultrasonic and radio frequency activity, the time delay between the radio frequency processed pulse and the ultrasonic processed pulse and the alarm status. The 4 level alarms are driven by the microprocessor.

Optical Fibre Connections

The digital input / output (I/O) between the microprocessor and the logging computer is via two optical fibres with standard RS232 port convertors at either end. This optical isolation allows safe data logging and trigger level adjustment if required. Furthermore, a modem may be connected to the logging computer to allow remote corrections to the levels and to the program.

Complete System Diagram

The complete system is illustrated schematically in Figure 4 showing the transducers, the head, the analogue processors, the microprocessor, the audible and visual alarms and the computer for on-line adjustment and data logging either locally or remotely.

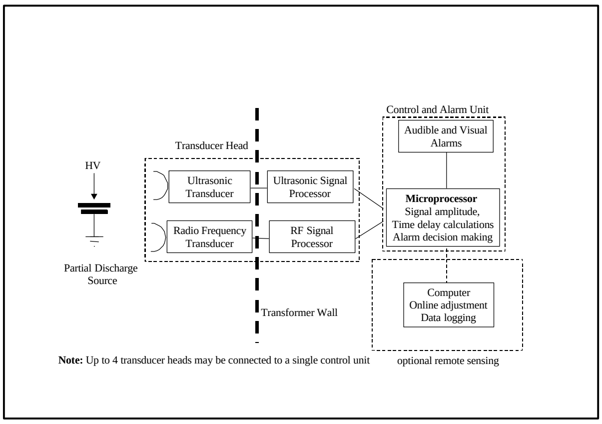

Figure 4 System Diagram

Probable Time Delay Calculation and Histogram

If an ultrasonic pulse is detected all radio frequency pulses are recorded up to 4 ms prior to the arrival of the ultrasonic pulse. These are combined in a time-delay versus count histogram as illustrated in Figure 5. As the time delay for a fixed partial discharge source does not vary, a peak will develop in the histogram while noisy interference will spread over the whole time period. This method allows the system to differentiate a relatively small number of partial discharges from a background of corona interference. In extreme cases a time delay may not be accurately resolved. However a large or medium amount of ultrasonic activity will still trigger the lower alarm conditions 3 and 4.

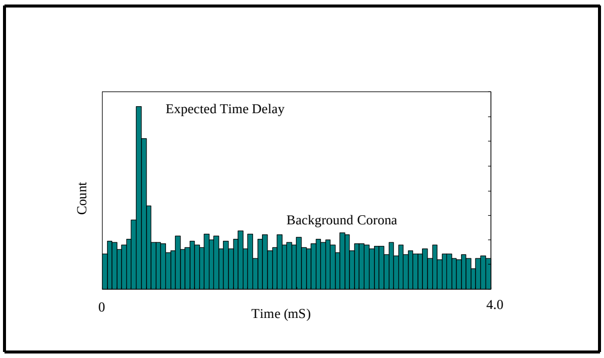

Figure 5 Time Delay Histogram

Alarm Criteria

Figure 6 illustrates the conditions for the four level alarms. In all cases, ultrasonic signals are detected.

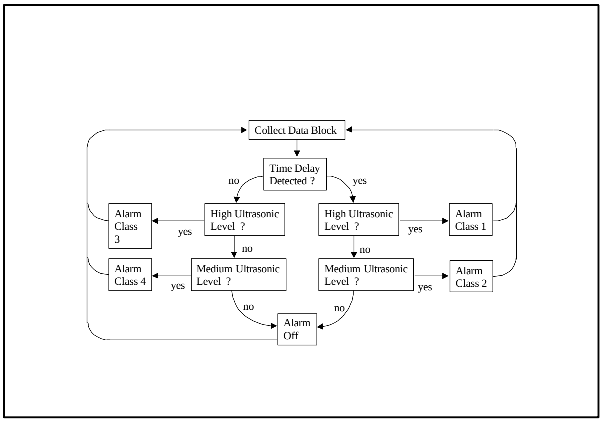

Figure 6 Alarm Criteria

The criteria, which we have found to be reliable in practice and not prone to give false alarms, are as follows :

Alarm Class 1 corresponds to a time delay detected and a high ultrasonic level
Alarm Class 2 corresponds to a time delay detected and a medium ultrasonic level.
Alarm Class 3 corresponds to no time delay detected but a high ultrasonic level.
Alarm Class 4 corresponds to no time delay detected but a medium ultrasonic level

Surge Protection

To protect the monitoring system against surges especially during high voltage and impulse testing of any transformer the following protective measures have been incorporated:

- Transorbs (transient suppression diodes) on the analogue electronic inputs and microprocessor.
- Metal oxide varistors on amplifier power supplies.
- Surge protector on the telephone lines.
- Surge protector on the computer mains supply.
- Uninterruptible supply for computer and modem.

- Optical isolation between radio frequency processor and microprocessor.
- Optical isolation between microprocessor and computer and modem.

This protection was proven during over - voltage and impulse testing of the re-wound Lepper transformer at Westinghouse (Villawood) prior to it being transported and installed at Tumut.

Injection Head.

In order to test the test the system two methods to produce "partial discharges" were developed: -

Artificial partial discharge injection

Artificial discharge pulses were generated by combining a reed relay, capacitatively coupled to the tank wall, and a piezoelectric element acoustically coupled to the transformer oil. The rapid electrical pulse generated by the relay produced a radio frequency signal while the piezoelectric element produced an ultrasonic wave to simulate the behaviour of a partial discharge.

Real partial discharge injection

A fine metal point / thin pressboard insulation/ metal plane was set up in the mineral oil and on application of gradually increasing AC voltages a source of partial discharges could be established. Once initiated it was found that the applied voltage could be reduced and the partial discharges could be sustained for several hours. This allowed extended testing of the entire detection and monitoring system. This method for producing real partial discharges was adapted to allow the source to be mounted inside a test transformer or coupled to a lead through plate and installed externally.

Test Tank and small 3 phase Test Transformer.

Early in the research program a rectangular steel tank was fabricated and filled with transformer mineral oil at the University. We designed this so it could house three sensing heads and one partial discharge injection head. Several investigations were carried out such as the effect on detection of attenuations and reflections caused by obstructions whist injecting simulated or real partial discharges. It was also used to perfect the design of the transducers and decide the best specification for the analogue electronics. This tank is still of value now the project is complete since it can be used for quality control of the entire system prior to delivery to a customer.

Later a small 3 phase 66kV test transformer was made available at Westinghouse and this allowed evaluation of the entire system whilst the transformer was in operation. There are positions for two sensing heads and one partial discharge injection head. It allowed a thorough investigation of the effect of corona interference via the bushings on the performance of the monitoring system. Setting the levels for the analogue electronics and deciding the criteria for the 4 level alarms was also investigated prior to trials on transformers in substations. This test transformer has been left with a complete monitor installation so that it can be demonstrated to potential customers.

Calibration

Attempts were made to obtain correlation between the amplitude of the ultrasonic pulse with the magnitude of associated partial discharge using a Robinson partial discharge instrument. Whilst rough trends were obtained measurement of the average ultrasonic amplitudes did not give unequivocal values for the partial discharge magnitude. This is why we had to seek more reliable criteria for the alarm conditions. The reason for poor correlation can be understood from the physical mechanism for generation of the ultrasonic pulse from a partial discharge. A bubble of gas develops in the oil which bursts .The energy released by the partial discharge is shared between the electrical energy in the radio frequency pulse and the mechanical energy to develop the bubble. The size of the bubble before it bursts depends upon the surface tension of the mineral oil and the hydrostatic pressure ie. depth in the oil. The bursting of the bubble results in the generation of the ultrasonic pulse. However if the bubble grows slowly the gas may dissolve in the oil, the bubble does not burst and there will be a radio frequency pulse with no ultrasonic pulse. Also depending upon the path of any ultrasonic pulse through solid obstructions (windings, iron core and paper insulation etc.) there will be varying degrees of attenuation. This will result in wide variation of the ultrasonic pulse amplitudes.

Installations

Several installations have been carried out in Australia most of which use remote monitoring: -

- Wellington (New South Wales).

This is a new 220 MVA transformer made by Asea Brown Boveri (ABB) for TransGrid and is monitored back in Sydney via modem connection over a distance of some 340 kM.

- Beaconsfield (New South Wales)

This is an old 330 kV transformer in a suburb of Sydney, which can now be, monitored in the substation office, at the university and at the central TransGrid office in the city.

- Tumut (New South Wales)

This is a 132kV Lepper transformer which was rewound at Westinghouse in Villawood near Sydney. The opportunity was taken to install the monitoring system whilst it was at Villawood during the re-wind. The monitoring system stayed on the transformer all through the approval high voltage and impulse testing. Thanks to the high level of surge protection we have incorporated in the system monitoring continued throughout the testing. The monitoring system proved to be of great value during this testing and detected and located partial discharges in the tap changer which proved to be faulty. The transformer has now been located in a small substation at Tumut (southern highlands of NSW) which serves areas in and near the Snowy Mountains. In this case, the modem connection is via a cellular telephone since there are no spare telephone lines and monitoring is taking place at Wagga Wagga and in Sydney.

TransGrid who own these transformers expect that early warning of breakdown will results in savings in maintenance and replacement costs, extension of the lifetime of high voltage transformers, improved safety and avoidance of environmental pollution.

Comparison of partial discharge monitor with dissolved gas analysis

Determination of the condition of transformers by analysis of the gases dissolved in the mineral oil (DGA) is quite different from monitoring the condition by the partial discharge method. Taking samples for gas analysis is usually done infrequently (typically once per year). However there are now on -line gas detectors available. The gases of importance are Hydrogen, Acetylene, Carbon Monoxide and Ethylene. These gases arise from different distributed sources throughout the transformer. The detection depends upon the absorption coefficient of the particular gas in the oil, it does not detect free gas. This gas absorption depends upon temperature which varies widely depending upon the location of the transformer and the loads to which it is subjected. The gas detector does not primarily detect partial discharge.

The gas detector therefore gives an integrated delayed response. Failure of a transformer is usually a localised breakdown and if this proceeds rapidly the gas detector could be too slow compared with the partial discharge monitor to give a sufficient early warning. Some difficulties were experienced with earlier versions of these on-line gas detectors but new versions are now available. . Some using Palladium electrode insulated semiconductors have to be changed at intervals because they become poisoned and lose sensitivity because of the effect of the sulphur in the mineral oil.

The two monitoring systems are complementary and considering the high capital and maintenance costs of transformers it could be worth installing both gas and partial discharge monitors.

Acknowledgments

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[1] Unsworth. J, Kurusingal J, James R, 1994 "On-line partial discharge monitor for high voltage power transformers."*Proc.4th ICPADM, Brisbane* pp. 729-732.