PRESSURE MONITORING TECHNIQUES OF VACUUM INTERRUPTERS

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ABSTRACT

There is a growing concern to monitor the pressure inside the vacuum interrupters for their integration into the network and to ensure their reliability. At present, traditional methods to measure degree of vacuum inside a vacuum interrupter cannot be applied universally and are generally design specific. Some of the methods described in the literature can only be applied in laboratory conditions and are not economical. There is, therefore, a need to have a pressure detecting technique which is more reliable, does not need electric or magnetic fields to be applied to the interrupter and could even be considered absolute. In this paper, novel methods for on-line pressure measurement have been described which are independent of the design, shape and size of vacuum interrupters. These novel techniques do not influence the pressure during measurement and therefore, could be applied universally. There is a need for a consensus on this issue between vacuum interrupter manufacturers.

INTRODUCTION

The global power transmission and distribution network is increasing rapidly. To fulfil the rising demand of the vacuum switchgear, while European and American markets have consolidated, new markets have emerged in Asia. The main disadvantages of vacuum switchgear are the possibility of loss of vacuum and the lack of a simple method for positively monitoring the condition of the degree of vacuum in the interrupter. In order to ensure the reliability [1] of vacuum interrupters in new installations, utilities and industries are beginning to think if it is possible to introduce online monitoring of the vacuum interrupters. This will not only help to know early detection of the performance of the vacuum interrupters in service but also help to ensure power grid stability by remote monitoring.

In addition, awareness to protect the environment is increasing. Electrical industries and utilities have reached a consensus either to remove or promote reduction of SF_6 gas in new switchgear installations. This is helping to develop vacuum interrupters for the market which has so far been dominated by the SF_6 switchgear. Excellent dielectric strength offered by vacuum also supports pushing vacuum interrupters in this market segment. As a result, significant investment and development work is being carried out to extend the range of vacuum interrupters from medium voltage to the high voltage operating systems up to 252 kVrms. This segment demands extreme reliability and stability of the products. As such, online monitoring of vacuum interrupters has become very important. Online monitoring will not only improve the reliability of the vacuum circuit breakers, but will also prevent serious faults and reduce maintenance costs in addition to helping the environment.

Requirements for monitoring are 1) it should not be affected by electrical noise pollution in their near vicinity 2) the monitoring technique should not be influenced by the continuous current or short-circuit current induced heat, magnetic field etc. and 3) be independent of different designs and makes of vacuum interrupters. Current interrupter designs have many layouts like:

- a floating centre shield which is exposed and can be used for electrical connection
- a floating centre shield which is housed within the vacuum interrupter and therefore, not accessible
- a polarised shield which is connected to the fixed contacts

A floating centre shield and a polarised shield configuration allow only the fixed and moving electrodes for access and monitoring. In addition, the measurement technique should be compatible if vacuum interrupter is housed in oil, SF_6 or solid insulation. This paper examines different techniques of monitoring pressure of new vacuum interrupters and possible new solutions which may be more accurate and applied universally.

CURRENT PRESSURE MONITORING TECHNIQUES

A Paschen curve would show that the breakdown voltage remains independent of the degree of vacuum from $\leq 5x10^{-4}$ torr. However, as pressure begins to deteriorate, the breakdown voltage performance also deteriorates. The vacuum interrupter losses its ability to switch power at pressures > 10^{-3} torr.

The vacuum interrupter looses its dielectric strength at pressures > 10^{-2} torr. This assumes that the interrupter is housed in ambient conditions with air around.

At present, traditional methods to measure degree of vacuum inside a vacuum interrupter are the power frequency voltage withstand test and magnetron gauge test (Penning discharge) [2-4]. While high voltage withstand test measures the emission current (or the leakage current) across the open contacts of a vacuum interrupter, magnetron gauge test measures the electric and magnetic field induced positive ion current.

The high voltage withstand test is a commonly adopted method to test vacuum interrupters during periodic maintenance by majority of customers. In this test, high voltage is applied across the interrupter having a contacts gap same as the operating arcing contacts gap of the vacuum circuit breaker. A ramp rate of 2-3 kV/sec is maintained till the maximum test voltage is reached. The interrupter is considered to have passed the test if the emission (leakage) current is low enough for it to withstand the high voltage without any breakdown for 1 minute. The high voltage withstand test only shows if the pressure inside the interrupter is above or below 10^{-2} torr.

Both emission current (withstand test) and positive ion current (magnetron gauge test) depend upon the internal layout and material of the vacuum interrupter components like centre shield, end shields, arc control contact diameter, contacts gap material etc. The magnetron discharge method cannot be applied universally for all the models and makes of vacuum interrupters and requires calibration for each interrupter types to be used. Both test methods can only be applied by taking the interrupter out of service and are therefore, not suitable for on-line monitoring.

Other techniques discussed in the literature include measuring pre-breakdown current, electromagnetic waves and floating shield potential measurement [5-9].

Measurement of pre-breakdown currents performed on vacuum interrupters' varying internal pressures has shown that high frequency (HF) impulse current at the voltage just below the pressure dependant breakdown voltage grow when the internal pressure is increased up to 10^{-3} torr. At this pressure HF current pulses of a higher magnitude often initiate the breakdown. However, the relationship between pre-breakdown currents and the internal pressure is not yet sufficiently determined and further investigation is needed. For example, pre-breakdown currents may depend upon parameters like contact material and its topology, nature of residual gas etc.

Electromagnetic waves are generated by vacuum interrupters while in service generally in the frequency range 2 kHz - 100 MHz. The frequency pattern and its duration change as the pressure degrades inside the vacuum interrupter. This technique has been proposed for online monitoring. Electromagnetic waves are generated by electrical discharges across the open contacts, while the contacts are closing or between the shield and the current carrying conductors. In a steady state, the high frequency emissions (also called discharges or noise) are continuous in nature. However, these emissions could be mixed-up with emissions from other events occurring either within the vacuum interrupter or in its vicinity.

Floating shield potential has been found to vary with the change in pressure inside the vacuum interrupter and is also proposed for on-line monitoring. In contacts close condition, if the pressure inside the vacuum interrupter deteriorates, discharges begin to occur between the electrodes and the arc shield which can easily be detected by a capacitive coupling sensor. Discharge has been found to initiate between 10^{-2} - 200 torr. However, this technique may not be suitable for interrupter designs where the shield may be absent, polarised or not approachable. In addition, variation in the surface quality of nearest conductors and shields, open/close contacts and sensor positioning may give considerable variation in the output results making the method questionable. Further, variation in the output voltage is very small in the pressure range 10^{-6}– 1.33 x 10^{-4} torr. This makes the detection equipment design expensive.

INTERRUPTERS IN OTHER ENVIRONMENT

For vacuum circuit breaker installations which use oil, solid insulation, SF_6 or other environment friendly gas such as CF_3I or similar mixtures, it may be difficult or relatively expensive to use existing on-line monitoring methods. In such installations, if the vacuum interrupter develops a sudden leak, its internal volume will have different constituents in its environment. This will also change the calibration curve and electromagnetic signature of the interrupter. Metallic equipment housing accommodating vacuum interrupters will allow the electromagnetic signatures to attenuate outside of the housing.

In practice, it is expected that once the leakage of surrounding environment occurs into the interrupter, its internal gas pressure will increase immediately to 10^{-2} - 10^{-1} torr. Pressure in this range gives the minimum of partial discharge (PD) inception voltage. Therefore, knowledge of PD signature of the interrupter under these environments is important.

LIMITATIONS OF EXISTING TECHNIQUES

For majority of pressure measuring techniques, the design layout of the vacuum interrupter components is critical to provide good resolution. Majority of vacuum interrupters which are manufactured today have self-aligned components and are therefore, suitable for single-shot seal-off. Depending upon the manufacturing technique, the tolerence on the alumina-ceramic envelopes vary considerably. Design tolerances of other components like floating centre shield, end metal plates etc. also vary proportionately. Arcing contacts erosion, changing internal surfaces due to deposition of metal vapours onto the arc shields, insulator housing etc. and radial magnetic induced rotating arc touching the arc shield change the interrupter layout further. It is, therefore, clear that the limits on interrupter components tolerances and change in the shape of the components vary considerably. Such variations introduce limitations and considerable inaccuracies in the pressure measurements especially when measuring emission current, Penning discharge induced current, shield potential, pre-arcing current etc. Moreover, majority of techniques do not cover the full operation range of pressure during the shelf life and operating life of the interrupter. In addition to the complexity and reliability of these pressure detecting techniques, the applied electric field causes a pumping action within the interrupter thereby, reducing its pressure. This pumping action complicates the interpretation of pressure evolution studies. Controlling the interrupter components tolerances pose substantial cost constraint on the interrupter type.

There is, therefore a need to have a pressure detecting technique which is more reliable, does not depend upon the in-service operating conditions and design layout of interrupter components and could even be considered absolute.

NOVEL PRESSURE MEASURING TECHNIQUES

SPINNING ROTOR GAUGE

Spinning rotor gauge technique is considered to provide absolute measurements of pressure and can also be applied for on-line monitoring [10]. Advantages associated with this method are:

- Measurements are not affected by the design and internal layout of the interrupter components
- The sensor tube attachment is robust when compared with other measuring devices and
- The method could be universally adopted for any design and make of vacuum interrupter

This technique has the potential to not only help on-line pressure monitoring of vacuum interrupters, but also help obviate the need for calibration for each vacuum interrupter type, thus, saving considerable cost.

Principle of operation

In this type of gauge a non-magnetic stainless steel tube (~ Ø8 mm) of sufficient length is attached to a vacuum system. The tube contains a steel ball of diameter 4-5 mm. A portable sensing head containing magnetic field coils is placed over the tube and the ball is levitated into rotation by a dc field and driven up to speed by an alternating magnetic field generated by the coils. The drive field is then switched off and as the ball slows down because of gas friction, a decrease in the rotational frequency, f, which is proportional to the gas pressure p, is measured as

$$p = -\frac{\Pi}{20} . \frac{\langle v \rangle . d . \rho}{\sigma} . \frac{df / dt}{f}$$

where d and ρ are the diameter and density of the ball. Parameter, σ represents interaction between gas molecules and ball surfaces and is generally considered unity. The measurement takes only a few seconds and could be repeated with an average time gap of 10 sec. In practice, the dc coil, ac coil and the permanent magnet could be epoxy moulded and slipped onto the tube from outside for measurement. The opening of the stainless steel tube into the interrupter is provided with a barrier to stop the steel ball falling into the interrupter main body.

The pressure measuring range is generally 10^{-7} mbar to 1 mbar with an accuracy of ± 3% of the read out value up to 10^{-2} mbar. The gauge has good long term stability (< 1%) over a year and does not affect the pressure in the device when a measurement is made.

PIEZOELECTRIC CRYSTAL OSCILLATOR

The piezoelectric crystal oscillator has a resonant frequency which is dependant upon the temperature and pressure [11-12]. The resonance impedance offered by crystal oscillator varies with temperature and pressure. This property can be used to detect the temperature and pressure inside the vacuum interrupter. Piezoelectric oscillator has the added advantage that it has high resistance to vibration and shock. Suitable materials as an oscillator are quartz, lithium niobate, lithium tantalate etc. but generally quartz is used. For a practical device and to increase the sensitivity of the quartz crystal oscillator, the miniature quartz crystal is shaped into a tuning fork. In vacuum interrupter housing, a miniature quartz oscillator can be mounted in a way which shields it from the metal vapour deposition but keeps it in close proximity with the environment inside the interrupter. In the housing, one end of the crystal oscillator can be brazed and the signal output taken to the control unit.

- Variation in the resonant frequency and hence the resonance impedance is directly proportional to the pressure inside the interrupter. The crystal oscillator can measure the pressure inside the interrupter enclosure from 10^{-3} torr to 1000 torr with an accuracy of ± 10%.
- There can be a reference oscillator used as well – like a hermetically sealed oscillator in a separate high vacuum housing placed in the close proximity of the interrupter. In this case, the device could be used for temperature sensing by comparing the signals of the two oscillators.
- Operation of the vacuum circuit breaker exerts transient mechanical force on the interrupter components especially fixed and moving contacts and the current carrying conductors. This transient nature of force can also be detected by the same crystal oscillator.

There is a large variation in the quartz crystal oscillator resonance impedance with temperature and pressure. This allows more accurate measurements to be carried out. Subsequent to any load switching or short-circuit switching operation, the temperature of the interrupter changes temporarily. Such changes could also be measured accurately.

The quartz oscillator has many advantages over other methods. For example, the measurements are not affected by the interrupter design layout or the operating conditions. The accuracy is such that no separate calibration is required. Because of this reason, this method could be universally adopted and become a standard not only for on-lime monitoring but also for in-house manufacturing process.

NANOWIRE SENSORS

There has been considerable progress made in the development of semiconductor, one dimensional, metal-oxide nano-structures which are sensitive to different gas species [13-14]. These sensors are based on CuO, ZnO,

SnO_2, In_2O_3, TiO_2, MgO, CdO, Ga_2O_3, Cu_2O, and WO_3. Some of these metal oxides are stable under higher temperature seal-off conditions of vacuum interrupter and therefore, can be adopted readily for on-line monitoring.

The nano-sized grains of metal oxides are almost depleted of carriers (most carriers are trapped in surface states) and exhibit much poorer conductivity than micro-sized grains, hence, when exposed to target gases, they exhibit greater conductance changes as more carriers are activated from their trapped states to the conduction band than with micro-sized grains. Nano-sensors offer ultra high sensitivity and operability in an ultra low power mode.

Sensitivity, response and recovery time, linear range, as well as limit of detection (LOD) are important performance parameters for gas sensors. Response times in the tens of seconds and recovery times as low as one minute have been reported for nanowire sensors which make them suitable for on-line monitoring. These sensors are gas specific and can be used to detect O_2 levels, for example, in case of an external leak. These need to be mounted in a shielded enclosure with gas specie detecting leads protruding out.

Recently, ZnO nanowire having average length and diameter of 5 µm and 30 nm, respectively has been fabricated on ZnO:Ga/glass substrates. By measuring the current–voltage characteristics of this sensor at low pressure the currents were measured as 17, 34, 57 and 96 nA for pressures at 1×10^{-3} torr, 1×10^{-4} torr, 3×10^{-5} torr and 5×10^{-6} torr, respectively [14]. These values suggest that the laterally grown ZnO nanowires prepared in this study are potentially useful for vacuum pressure sensing. More studies need to be carried out to examine their suitability for vacuum interrupters.

CONCLUSION

New emerging applications of vacuum switchgear in power generation and transmission have a focus on reliability, safety, on-line monitoring and environment. In-service operating conditions do not allow conventional pressure monitoring techniques to provide accurate information on vacuum interrupter environment. Methods like, spinning rotor gauge, piezoelectric crystal oscillator and nanowire sensors offer unique solutions. These techniques are not design or interrupter layout specific and therefore, could be applied universally. The adaptation of one of the novel techniques will not only help on-line monitoring of vacuum interrupters in service but also provide solution for pressure measurements to be carried out during in-house post seal-off processing of vacuum interrupters.

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