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COMPARISON OF VARIOUS TESTING METHODS TO DETERMINE VACUUM PRESSURE IN THE VACUUM INTERRUPTER BOTTLE

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Abstract - *In this paper, the comparative study of different methods to measure the VACUUM level inside the VACUUM Interrupter is carried out. The requirement of measurement of VACUUM level is necessary to know the health of the VACUUM interrupter. Normally adopted methods for the determination of VACUUM level are required to be compared for the accuracy of the measurements, at manufacturers' end as well as at the field. The test setup at manufacturers' place is not available at the site or field. Hence the more practicable and easy to operate as well as a handy test system is always preferable in the fields. This paper provides comparative merits and de-merits of various test methods, their principles of operation, and idea about the physical size.*

***Key Words*: 760 mm of Hg = 1 Atmospheric pressure at sea level, = 1 Bar pressure. 1 millibar = 760/1000 = 0.76 mm of Hg. 1mm of Hg = 1Torr Vacuum.**

1. INTRODUCTION

Vacuum interrupters are sealed for life vacuum devices which perform current interruption at the next available current zero once the contacts have been separated. Due to the extremely high dielectric level of a vacuum, it is normally necessary to open the contacts only 6-8mm apart. The quality of a vacuum is indicated by amount of air matter remaining in the vacuum bottle, so that a high quality vacuum needs very negligible air matter left in it (Vacuum bottle). This negative pressure or vacuum is measured by referring following;

1. Absolute vacuum. (760 torr).
2. Temperature.
3. Chemical composition of components of vacuum bottle.
4. Mean free path (MFP) of residual gases, which indicates the average distance those molecules will travel between the two electrodes & make collisions with each other. As the gas density decreases, the MFP increases and continuum assumptions of fluid mechanics do not apply. This vacuum state is called "high vacuum" (more than10^{-3}torr) and the study of fluid flows in this regime is called particle gas dynamics. Electrical insulation in vacuum follows the *"Paschen curve"* shown below

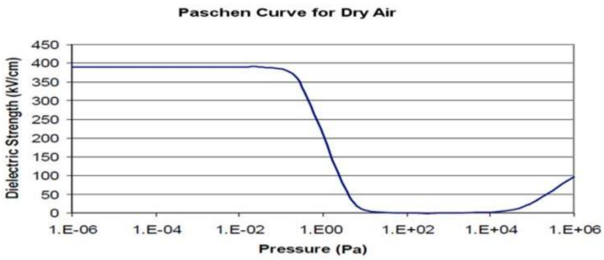

Fig -1: Paschen Curve for Dry Air

Paschen did original experimental research and discovered that the dielectric strength (*V*) of a gas is a function of the gas pressure (*P*), the distance between the two electrodes (*d*) and the type of gas.

V= apd/ ln (pd) b

Where *a, b* are the constants derived for dry air.

Normally for gaseous insulation we are concerned with the right hand side of the curve showing for a gas with increasing pressure. However for vacuum, we are interested in the left hand part of the curve. The curve shows that the dielectric level of air starts to increase dramatically as the pressure drops below approximately 10Pa (10^{-1} *mbar*). It continues to rise swiftly until pressure reaches approximately 10^{-1} *Pa* (10^{-3} *mbar*) and then remains fairly steady at slightly less than 400kV/cm (approximately 1000kV/in).Any pressure better than 10^{-3} *mbar* has no effect on the dielectric level of the vacuum gap. As pressure begins to deteriorate, the breakdown voltage performance also deteriorates this means that any change in pressure which remains lower than 10^{-3} *mbar* will have no effect on the performance of the vacuum interrupter or switch. This is termed as the "limiting value".

The interrupting capacity in a VI will vary depending on

1. Contact design
2. Contact separation
3. VACUUM level.

The contact design and separation are design features for any given VI. However from the previous discussions we can say that the interrupting ability will be very high and very sensitive to the pressure (vacuum) level inside the vacuum interrupter. This leads us to the detailed study of vacuum level present inside the vacuum interrupter and various methods to measure the vacuum level inside the VI.

- **Level of vacuum dielectric medium inside a VI:**

According to *the theory of Townsend discharge*, which is very common in gas dielectrics, the development of current in a gap relies upon the movement of charged particles. In the absence of such particles, as in the case of perfect vacuum, there should not be any traces of conduction and the vacuum ought to be a perfect medium of insulation. The level of vacuum dielectric medium in VI depends on the impedance offered by the vacuum medium. This impedance mainly depends upon the availability of the free charge carriers in the medium. In the vacuum Dielectric medium, the role of charge carriers is played by, the free residual air particles in the vacuum. This is because, it is practically impossible to create absolute vacuum inside the VI.

Level measurement of vacuum includes two parameters

1. Availability of free charge carriers.
2. Pressure of vacuum.

The 'Level' of the vacuum medium does not mean the B.D.V. of the medium for defined gap. It is to be defined as the Quantum of charge carriers present in vacuum medium.

Based on the above discussed facts various methods are introduced to know the amount of vacuum available inside the VI, which are studied comparatively in the succeeding chapters. These methods are listed below.

1. Use of Gaga ohm-meter.
2. Use of logarithmic amplifier.
3. Use of vertical electrostatic field in parallel with static magnetic field.
4. Use of magnetron.
5. Inverse magnetron method.

- **Use of Gaga ohm-meter.**

✓ It is the most basic and common method.

✓ This method has a basis of the fact that the strength of vacuum dielectric medium in VI depends on the impedance (resistance) offered by the vacuum medium and this

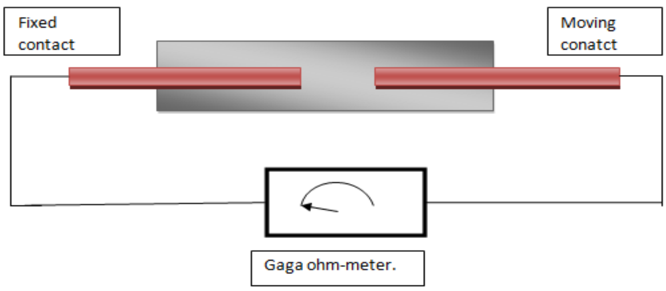

Fig -2: Gaga Ohm-meter

Mainly depends upon the availability of free charge carriers in the medium. Gaga ohm-meter is a high resistance measuring meter which can measure resistances in the range (10^6 ohm to 10^9 ohm).

✓ The VI is connected across the Gaga ohm-meter and the resistance value can be seen on the meter display.

✓ The level of vacuum present inside the VI bottle will be dependent on the amount of resistance measured by the ohm-meter. According to the result of resistance displayed, the strength of vacuum medium is calculated. This method is used by site (field) engineers only.

- **2. Use of logarithmic amplifiers.**

✓ The concept behind this method is to develop the capacitance between the two electrodes (contacts) and measuring the leakage current due to free charge carriers present inside the VI.

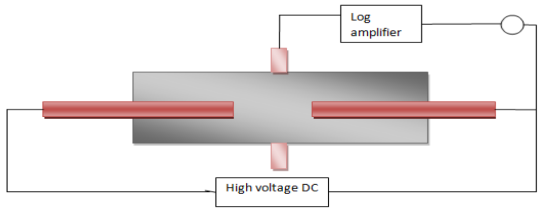

Fig -3: Use of logarithmic amplifiers for Vacuum Level Measurement

As the suspended particles are in small quantity the leakage current due to these particles will also be in small amount, of the order of nano amperes. In this method a high DC voltage is applied across the open contacts of VI and the shielding electrode is kept at ground potential as a reference voltage then leakage current and its watt component using its relation with *tan δ* (dielectric dissipation factor) then using logarithmic scale the calibration is brought to the measurable value on the meter.

✓ ***Few drawbacks of this method are listed below.***

✓ This method requires ideal grounding for calibration of reading which leads to operators' safety issue and the insulation co-ordination of the test setup.

✓ Rounding off errors affects the accuracy.

✓ Critical in measurement and calibration.

✓ Analog instruments give better performance with this setup but scale crowding gives inaccuracy in reading and Digital instruments are not made sensible for the requirement of this function as ICs etc. get affected by High DC field.

3 Use of vertical electrostatic field in parallel with static magnetic field

✓ In this system, the open contacts of VI bottle are subjected to high Voltage DC supply to establish the capacitance between two contacts. The magnetic solenoid coil terminals are connected to the high DC current supply to develop heavy magnetic flux. Their **joint action** on free air particles, make them to get **polarized** towards shielding electrode kept at reference potential, by measuring the current through it and calibrating the same, the strength of the field is determined.

✓ The fundamental principle used behind this method is based on the Faraday's Law, saying that 'whenever a current carrying conductor is placed in the magnetic field a force gets exerted on it. In this

case, the charged particles and their free movement in a medium can be treated as instantaneous current and there is a development of MAGNETIC DRAG according to the effect of '**Lorentz Force**' which gets developed on a charged particle when a charged particle moves in a region where both the magnetic and electric field are present.

- ✓ The **equation** of this motion for the **charge** is given by the relation,

$$m(dv/dt) = QE + Q(V*B)$$

- ✓ This type of equipment is used by SEMENS ltd. Which require + 5KV DC supply with 5mA across the VI open terminals and 50 Ampere, 40 V supply through Solenoid coil to develop magnetic field of 1380Gauss.
- ✓ The limitation of this method is that it is useful for the Double Ceramic VI which can provide shielding electrode link at outer periphery.

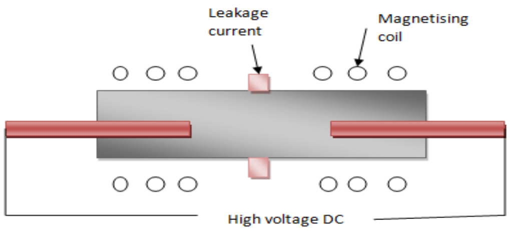

Fig -4: Use of vertical electrostatic field in parallel with static magnetic field

Having known the fact that both the Magnetron and Inverted Magnetron methods are the subtypes of the cold cathode ionization gauges, we will briefly discuss about the Cold cathode gauges first. **Cold cathode ionization vacuum gauges** essentially consist of only two electrodes, a cathode and an anode, between which a high voltage is applied via a series resistor. Negatively charged electrons leave the cathode through field emission, moving at high velocity from the cathode toward the anode. As they travel this path, they ionize neutral gas molecules, which ignite a gas discharge. The measured gas discharge current is a parameter for pressure. Several varieties of Cold Cathode Gauges are used for vacuum measurement including *the penning, the magnetron, the inverted magnetron and double inverted magnetron*. All CCGs utilize crossed electric and magnetic fields to trap electrons. The high voltage range from 2-6 kV and the magnetic field 1-2 kG. The electron plasma which is responsible for ionization originates from the random release of electrons at the cathode caused directly or indirectly or due to some other reason. A discharge slowly builds inside the ionization volume to the point where the entry of new electron into the plasma is limited by space change repulsion. At pressures below 10^{-4} *torr* the discharge is practically pure electron plasma. The electrons move in cyclonical jumps, circling about the anode and during part of each jump they have sufficient energy to ionize gas molecules through electron impact ionization. The probability of collision is proportional to the gas density. The slow ions generated by this ion collection process is measured and used as indirect indication of gas density and pressure. The typical operating range of a CCG is between 10^{-2} to 10^{-9} *torr* the ion-induced current is not linearly related to the pressure in the chamber. Rather the relationship is exponential and complicated by the presence of spurious discontinuities in the current versus pressure characteristics. The number and size of discontinuities depends on gauge design, with the inverted magnetron being the least susceptible to this problem. Elimination of discontinuities has been a major challenge to designers of CCGs since their conception. The non-linear relationship between current and pressure is a disadvantage that complicates the reliability of pressure measurements, particularly below 10^{-9} *torr*. Repeatability is about $\pm 5\%$ and sensor to sensor matching is within 20-25 % for inverted magnetrons. Stable operation appears to be possible over periods of several years under clean, low pressure vacuum condition. However contamination can cause failure of CCG. The electronics required to operate a CCG are usually much less expensive.

- **4 Use of magnetron.**
  - This method is a modified form of the penning gauge method which is invented by Francs Michel Penning, for the vacuum level measurement, which works on the penning discharge principle.
  - *Penning discharge principle* Charged particles (ions) can be generated from high voltage supplied across an open vacuum interrupter. When a strong magnetic field is applied, these ions will move, thereby, producing a current across the open contacts. This ionization current is directly proportional to the pressure inside the vacuum interrupter. With a known pressure-ionization current curve, the pressure inside a vacuum interrupter can be easily determined through the Penning Discharge principle.
  - In particular in Penning gauges, which use an axially symmetric magnetic field to create path lengths for electrons that, are of the order of meters. In a Penning gauge, design features are used to ease the set-up of a discharge path. For example, the electrode of a Penning gauge is usually finely tapered to facilitate the field emission of electrons.
  - The initial Penning design (cylindrical anode and end plate cathodes) was neither precise nor accurate and it was replaced by other geometries.
  - However, *the name Penning is still used even for magnetrons with central wire or ring cathodes*. The operating voltage is limited (typically to ~2kV) to avoid field emission effects that cause increases in the ion current unrelated to pressure.
  - While the newer magnetron designs are satisfactory, they are limited to the top of the high vacuum range and attract little commercial attention.
  - Magnetron also uses the Penning discharge principle to determine the level of vacuum inside a vacuum interrupter.
  - This type of gauge commonly referred to as a cold cathode magnetron ionization gauge has been

developed to a high state of perfection by P. A. Redhead in the 1950s.

- This gauge consists of a pair of plates (electrodes) mounted within the vacuum envelope between which a static electric field is generated. The electric plates are immersed in a magnetic field aligned substantially at right angles to the static field. Through the application of the static and magnetic fields of the proper field strength, any stray electrons within the confined space will not travel directly to the positively biased plate (anode), but will travel in cycloidal or elliptical paths within the confined space. At low pressures, for example at pressures of the order of 10^{-4} *torr* and below, relatively few gas molecules are present in the vacuum space, therefore the tortuous route taken by the electrons greatly enhances the number of collisions with the remaining molecules, so as to enhance the probability of an ionizing collision. Since the pressure of the confined space is determined by measuring the number of positive ions within the vacuum envelope, it is obvious that any method which increases the ratio of ions/molecules (or ions/atoms) will also magnify the sensitivity of the measuring device.
- The current produced in a magnetron type gauge is proportional to an exponential of pressure. Thus, by measuring current the pressure of the vacuum level can be directly obtained

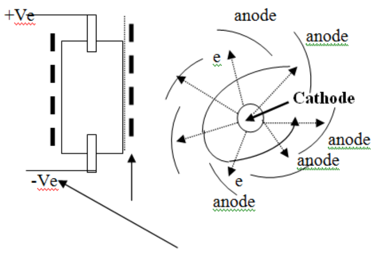

Fig -5: Magnetron Method

- This current is very high (1A or so) it has high sensitivity and therefore discharge current may be inexpensively measured without an amplifier down to 10^{-4} *torr* .
- The old magnetrons had a technical and logistical problems associated with them but with industry improvements in components and manufacturing capability, magnetrons such as the one shown at the right in Figure, are now coming onto the market for field use. It is small and portable and will retain calibration with only the normal procedures as specified in industry standards for field testing.

Fig -2: Portable Magnetron (right) with Test Stand (left)

- Discharge is generally not stable in cross field gauges. In early designs the discharge became erratic below 10^{-3} *torr* and was often extinguished completely to 10^{-4} *torr* Therefore better designs were invented with the aim of increasing the active volume of the discharge and reducing discontinuities.
- Cannot be applied universally for all the models and makes of VIs and requires calibration for each interrupter types to be used.
- Can only be applied by taking the interrupter out of service and are therefore, not suitable for online monitoring.
- At high pressures the cathode erodes and the production of secondary electrons depends on the surface of the cathode and it has to be cleaned quite often to get reproducible results.
- They don't work if the vacuum is too good.(they stop conducting when the pressure drops below 10^{-7} *torr*

5 Inverted magnetron method

- In the magnetron method the measured gas discharge current is a parameter for pressure. However only few molecules are ionized in the case of straight electron trajectories, which results in lower sensitivity and interruption of the gas discharge at approximately 1 Pa.
- A design that avoids this disadvantage is the Hobson and Redhead inverted magnetron and it has same advantages as magnetron method.
- The Inverted magnetron, also called a Redhead gauge.
- Inverted magnetrons can measure from 10^{-3} torr down to 10^{-12} torr
- A metal pin (anode) is surrounded by a rotationally symmetrical measurement chamber (cathode). An axially magnetized cylindrical, permanent-magnet ring is placed on the exterior of the measurement chamber to generate a magnetic field within the chamber.
- Its electrode geometry is evolved from penning configuration. (Anode changed to a rod and auxiliary (shield) cathode is added.)
- It requires DC voltage of about 4kV.
- The ion current and pressure are not linearly related therefore it measures pressure indirectly.

- Newly designed inverted magnetrons produce accurate, repeatable pressure readings and may be used in dirty or corrosive applications.
- These features make them perfect for use in vacuum furnaces and other industrial systems, where ruggedness is of prime importance.
- Design permits broader measurement range, faster start-up, superior accuracy and repeatability.
- Electrons are trapped more efficiently than in original penning gauge, therefore starting conditions are improved.
- The relations between P, B, and V follow reasonably the theoretical predictions and the discharge is stable to much lower pressures.
- At pressures of 10^{-10} *torr* error may be as high as the order of magnitude.
- It can reduce stray field to only a few Gauss.

6 Conclusion:

After going through the operating principles of operations and the techniques of the above said methods and making the comparative study of them, I want to put forward my observations as a conclusion.

1. In case of *Gaga ohmmeter*, resistance to be measured is in GΩ i.e. very large therefore any small fraction of change in pressure (particles present between the contacts) will not be detected which is being the drawback of this method.

2. In the second method next to this, capacitance is developed between the contacts and the small amount of leakage current is amplified with the help of logarithmic amplifiers but crowding of scale leads to rounding off the errors and hence affects the accuracy of vacuum level detection.

3. Relatively speaking in the third method where vertical electrostatic field in parallel with static magnetic field is used capacitance is developed between the two contacts and charged particle moves in a region where both the magnetic and electric field is present. The instantaneous current due to this is then measured, hence overcoming the drawback of logarithmic amplifiers, but this method is useful for the Double Ceramic VI only which can provide shielding electrode link at outer periphery.

4. Seen against the use of vertical electrostatic field in parallel with the static magnetic field the Magnetron method has been introduced based on penning discharge principle with a change in field system i.e. cross field is used. In this method the current is high (up to 1A) so that we can measure this current without amplifiers down to 10^{-4} *torr* These magnetrons don't work if the vacuum is too good and it has other many drawbacks associated with it such as it is not suitable for online monitoring, it needs to be calibrated for each type of interrupters, it requires regular cleaning of the cathode surface. Whereas Inverted magnetrons can measure pressure from 10^{-3} *torr* down to 10^{-12} *torr* this is being a broader measurement range. It can produce accurate, repeatable pressure readings and may be used in dirty or corrosive applications.

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