



Review of Modern Switchgear Failure Monitoring Technologies

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ABSTRACT: An Air Insulated Switchgear forms the backbone of power distribution network. Most of these switchgears under operation have already crossed their service-life period. Such switchgears are sensitive to its operating environmental conditions. The failure of switchgear equipment can be catastrophic and fatal to human life. The weather changes taken place within past decade has imposed additional performance burden on these switchgears [4]. Hence it becomes essential to monitor switchgear operating condition to reduce risk of unexpected failures, maintains continuity of service during measurement and helps in scheduling proactive maintenance activities. This paper discusses about need and operational details of such switchgear monitoring technologies.

KEYWORDS: air insulated switchgear, partial discharge, RFID, temperature, humidity, ozone

I. INTRODUCTION

An electrical switchgear is a centralized collection of fuses circuit breakers and switches which aids in isolation, protection and control of electrical load. An Air Insulated Switchgear (AIS) is most widely used switchgear for Medium Voltage (MV) and High Voltage (HV) applications due to its lower initial investment. The average service life of an AIS is around 25-30 years. Most of the switchgears in service today are more than 25years old [20] and hence has approached end of their service life. Such aged switchgears are prone to catastrophic failure when subjected to abnormal environmental conditions and thermal overloading.

The “IEC 62271-1: Standard for High Voltage Switchgear and Controlgear” describes the normal environmental conditions that should be maintained by switchgear operator in order to ensure safe and reliable operation of the switchgear [5]-[9]. The Table I gives an overview of the failure causes as reported by IEEE “Gold Book”, IEEE Std 493-2007, “IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems”, Annex E, table XVIII, page 479 [19].

TABLE I. FAILURE CAUSES IN AIR INSULATED SWITCHGEAR

Causes of failures in air-insulated switchgear	Share of air insulated switchgear failures
Thermocycling	7%
Mechanical structure failure	3%
Mechanical damage from foreign source	7%
Shorting by snakes, birds, rodents, etc.	3%
Malfunction of protective device	10%
Above normal ambient	3%



Exposure to chemicals or solvents	3%
Exposure to moisture	30%
Exposure to dust or other contaminants	10%
Exposure to non-electrical fire	7%
Normal deterioration from age	10%
Severe weather condition	3%
Others	4%

Source: IEEE 493 Gold Book, Annex E, table XVIII, page 479

A. Temperature Related Failure of Switchgear:

As the power system is continually expanding, the thermal overloads on the switchgear has become frequent. The operating temperature of busbar joint is critical point for temperature related failure. The joint of the busbar acts as heat sink for busbar system. Operation of busbar joints at high temperatures leads to their oxidation. Oxidation further impedes the ability of the joint to dissipate heat leading to overheating and reduction in tensile strength of the joint. Also, unbalanced loading of the three phase system results in uneven heating of busbar joints.

The operating temperature range plays a very crucial part at an event of short circuit. After an event of short circuit, after the circuit breaker (CB) interrupts the fault, the busbar temperature rises rapidly as the heat cannot be lost to the environment in the short span of time. Keeping this condition in mind, the switchgears are designed to allow max. temperature rise of 100°C above normal max. operating temperature (i.e. up to 180°C-190°C) after short circuit clearance by CB, such that the tensile strength of the busbar joint is maintained. That is the reason busbar joints are normally operated in temperature range of 80-90 °C [3]. In many switchgears, joints of the busbars are usually plated with metals like silver or tin to prevent its oxidation and thus enables higher operating temperatures. But it is not recommended to exceed the temperature owing to limited heat dissipation capacity of the cabinet and safety of the other temperature sensitive electronic equipment in the switchgear.

The service life expectancy of insulation and busbar joints can be estimated by the empirical formula known as Arrhenius Equation:

$$L=L_0 \times 2^{\frac{T_{Max}-T_0}{10}} \dots\dots\dots(1)$$

Where,

L= Expected service life at operating temperature

L₀=Expected service life at max. operating temperature

T_{Max}= Max. operating temperature

T₀= Operating temperature (ambient temperature + inherent temperature rise)

Consider,

Expected service life at max. operating temperature (L₀)= 25yrs.

Max. operating temperature (T_{Max})= 80°C

Operating temperature(T₀) =90°C

The expected service life (L)= 25 × 2 ^{$\frac{80-90}{10}$}

= 12.5 years

The above result is the indication that, rise in operating temperature by every 10°C above max. operating temperature results in reduction of switchgear life by factor of 1/2. Conversely, reduction in operating temperature by every 10°C below max. operating temperature results in extension of switchgear life by factor of 2. The Fig. 1 depicts the dependency of switchgear life on operating temperature.

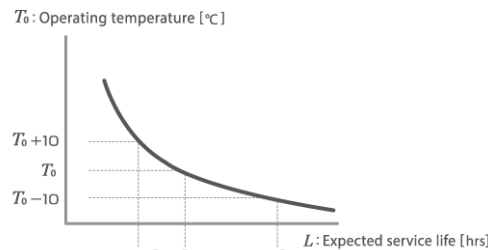


Fig. 1. Plot of Operating Temperature v/s Switchgear Life

B. Humidity Related Failure of Switchgear:

Presence of high humidity in the busbar chamber increases chances of condensation on busbars. This can cause failure of bus support insulator and can also initiate corona discharge. The HV busbars set up a non-uniform electric field in the busbar chamber. The air surrounding the busbars hence get stressed unequally. Generally, the atmospheric air breaks down when voltage gradient exceeds 3 kV/mm. This gradient is easily exceeded on sharp edges/corners in busbar resulting in corona discharge. Also, the gradient is easily exceeded in presence of condensate on surface of the busbar.

The corona inception voltage rises with humidity. But at higher humidity, condensation results in non-uniform electric field at HV busbar surface leading to reduction in corona inception voltage [8-9]. The Fig. 2 depicts the dependency of corona inception voltage on relative humidity. The corona discharge leads to decomposition of atmospheric air in switchgear leading to production of gaseous by-products like ozone (O₃) and nitrous oxide (NO₂). Ozone is highly poisonous gas and acts as strong oxidizing agent. It oxidizes polymeric insulation and responsible for busbar joint oxidation. Reaction of nitrous oxide with moisture produces Nitric Acid (HNO₃) which has ability to corrode busbar conductors and switchgear cabinet.

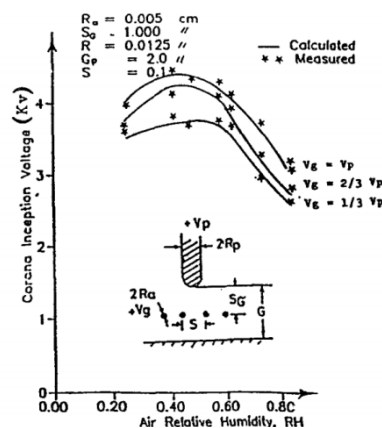


Fig. 2. Plot of Corona Inception Voltage v/s Relative Humidity

The moisture in combination with dust deposited on insulator surface can result in increase in insulator leakage current and can lead to flashover. Polymeric insulation can get hydrated when contacted by moisture leading to surface tracking on its surface [7]. The Fig. 3 depicts failure mechanism operating inside a switchgear.

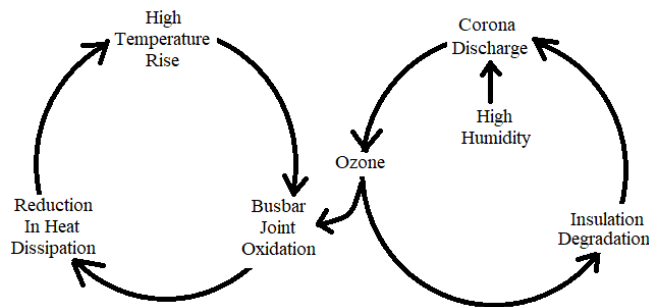


Fig. 3. Failure Mechanism

II. SWITCHGEAR MONITORING TECHNOLOGIES

There are few innovative switchgear condition monitoring systems described in the literature [10-13]. The paper [10] proposes a wireless temperature monitoring system for substation. The temperature monitoring system uses Zigbee communication protocol to form a wireless network of temperature sensing nodes. The sensor node is composed of DS18B20 temperature sensor, CC2430 RF transceiver and two AA batteries. Each of these temperature sensing nodes is situated on the busbar joint. The sensing node is expected to remain active for the period ranging from 6 months to 2 years. The papers [12] proposes a network of wireless temperature sensors based on infrared technology powered by current transformer (CT) based energy harvesting technique. Another paper [13] also proposes use of CT to power-up wireless temperature transmitter terminal which uses Zigbee protocol.

The Zigbee based wireless temperature sensor technology is also commercially available. The main disadvantages of such a sensor system being the interference caused by Wi-Fi-enabled devices like routers, cellphones, etc. operating at 2.4GHz radio frequency band.

Surface Acoustic Wave (SAW) Sensor Technology: This sensor belongs to class of sensors known as micro-electromechanical systems (MEMS). The sensor operation is based on modulation of surface acoustic waves to sense a physical phenomena. The sensor transduces an electrical signal into mechanical waves and sets the wave onto the piezoelectric substrate. These waves are influenced by physical phenomena surrounding the sensor. This influence on sensor results in change in amplitude, phase or time-delay between input and output electrical signals which is used to detect presence of physical phenomena.

The SAW (Surface Acoustic Wave) wireless sensor technology is commercially available for switchgear temperature monitoring. These sensors are not versatile in terms of form factor, hence cannot be mounted on all types of switchgear surfaces. The deployment of high number of these sensors demands many antennae because limited number of sensors can be addressed per antenna resulting in high investment cost of the system. This also restricts ease of expansion of sensor network in future. The sensor may give false positive output at an event of transient (lightning, arcing, switching, etc.).

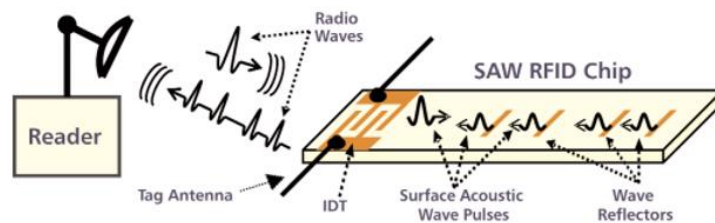


Fig. 4: SAW RFID Operation

SAW RFID Operation: The reader transmits an RF pulse towards SAW chip. The RF pulse is caught by tag antenna and then the pulse is converted to nano-scale Surface Acoustic Wave (SAW) by special structure called IDT (Interdigitated Transducer). The nano-scale waves travel passed acoustic wave reflectors on the SAW chip. These wave is reflected to form uniquely encoded acoustic wave pulses which then travel back towards IDT. The IDT converts these waves back to encoded radio RF reply transmitted to the reader.

RF Micron’s IC RFID Sensor Technology: These battery-less Smart Passive Sensors (SPS) enables to design a practical monitoring solution which was not available previously. These type of installations are low cost, wireless, allows many monitoring nodes and are maintenance free. Such sensor nodes utilizes patented Magnus-S family of ICs designed for use with EPC Class-1 Gen2 standard.

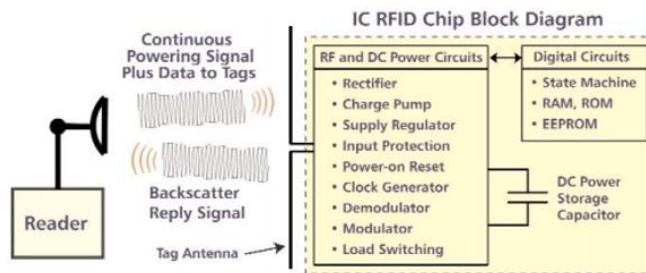


Fig. 5: IC RFID Operation

IC RFID Operation: The reader continuously emits modulated RF waves towards the tag. The tag has an internal rectifier which then rectifies the incoming RF wave and applies it across an internal storage capacitor. The stored power is then used to power-up the IC. The IC remains in ON -state till it receives sufficient RF power from the reader.



Fig. 6: SAW Sensors



Fig. 7: RF Sensor Tag

TABLE II. RF Micron v/s SAW Sensor Comparison Table

	RF Micron IC RFID Sensor	SAW RFID Sensor
1	Wider Range in the Sensor Form Factor	
	These sensors come with a variety of form factors and attachment mechanisms which enables one to monitor busbars, cable heads and contactor assemblies. The sensors can be lug mounted or adhesive attached to the surface of interest.	The SAW sensors have a single form factor making them unsuitable for cable heads and contactor assemblies. The SAW sensors are not low profile as RF Micron sensors.
2	Higher Number of Uniquely Addressable Sensors	
	Each RF Micron sensor is uniquely identified via 128bit EPC (Electronic Product Code).This code is programmed onto the sensor post production. A switchgear typically has 20-30 critical monitoring points and EPC addressing can handle these many no. of sensors.	Each SAW sensor is identified based on a unique backscattering pattern which is dependent on sensor construction. Hence each sensor has to be manufactured differently to have a different backscatter pattern which limits the no. of sensors that can be deployed in the switchgear per reader antenna. Typically 12 SAW sensors can be deployed per reader antenna. Which means additional antennae are required to incorporate more no. of sensors, increasing the cost of installation .

3	Robust and Efficient Communication Protocol between the Reader and Sensors	
	The communication protocol uses digital signal modulation techniques and error checking mechanisms, which ensures robust communication. This type of communication prevents transmission errors incurred due to electrical transients or interference from other sensors. Also the protocol allows a selected group of sensors to respond to the reader command, avoiding no. of read commands and improves throughput.	The communication protocol used here uses analog modulation techniques. Hence the output of these sensors is subjected to false positives in event of high frequency transients (arcing, switching). Interference due to neighbouring sensors is common.
4	Smart Features on the Reader	
	These sensors report back Receive Signal Strength Indicator (RSSI) which can be used by the reader to decide if a temperature reading qualifies. If the RSSI value falls out of bounds the re-reading of the sensor can be initiated by the reader.	These features are notably absent in SAW-based solutions.

III. INSTALLATION & WORKING

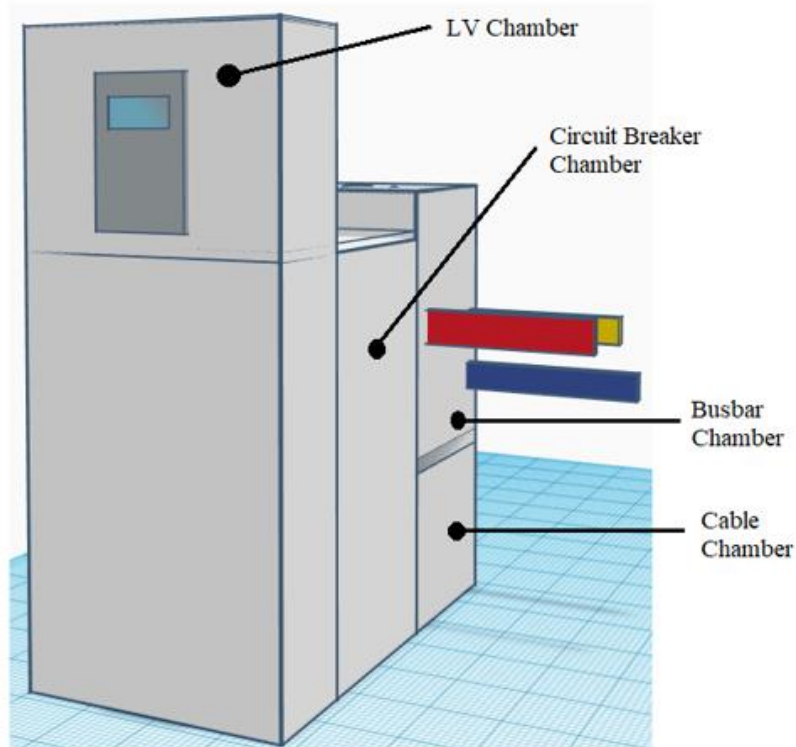


Fig. 8: Air Insulated Switchgear

Busbar Compartment : The busbar compartment houses the main busbar system, which is connected to the fixed upper isolating contacts of the main switchgear apparatus by means of branch connections. The main busbars are made of high conductivity copper. Depending on the current rating, single or double busbar configurations are preferred.

Cable Compartment :

The cable compartment can houses following components:

- Branch connections
- Earthing busbar
- Earth switch
- Power cables
- Surge arrestors
- Instrument transformers (current transformers, voltage transformers)

Switching Compartment / Withdrawable Equipment Compartment: The compartment houses a circuit breaker(CB). This compartment has bushings containing fixed contacts for CB to cable compartment. These bushings are made up of cast resin. All the bushings are covered by metallic shutters. These metallic shutters automatically open and close when CB is moved from test position(rack out) to service position(rack in).

Low Voltage Compartment / Control Compartment: The LV compartment houses all low voltage control equipment and wiring and DIN rail mounted terminal blocks.

The Smart Passive Sensors (SPS) will be located in the busbar chamber. The sensors are based on RF (Radio-Frequency) Energy Harvesting Technology. The sensors are hence self powered. These sensors will be installed as shown in the Fig. 9.

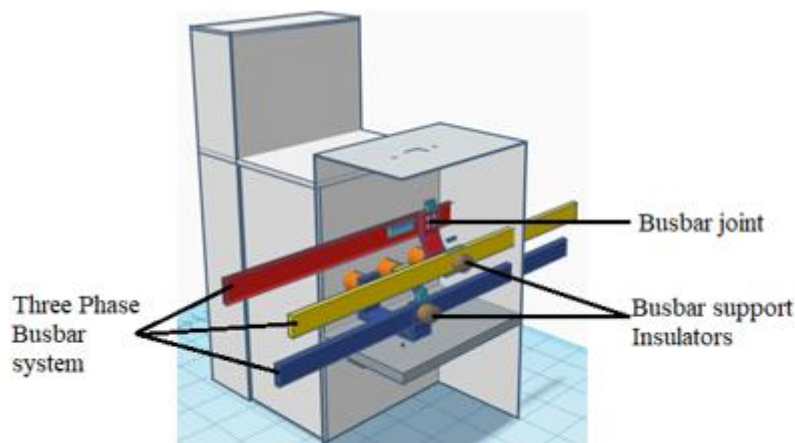


Fig. 9: Open view of busbar chamber

The exact placement of smart passive sensors is indicated in Fig. 10 & Fig. 11

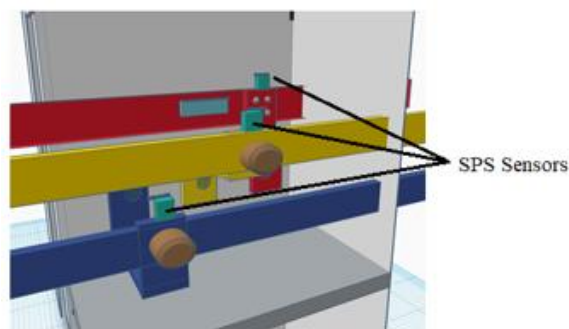


Fig. 10: Sensors placement

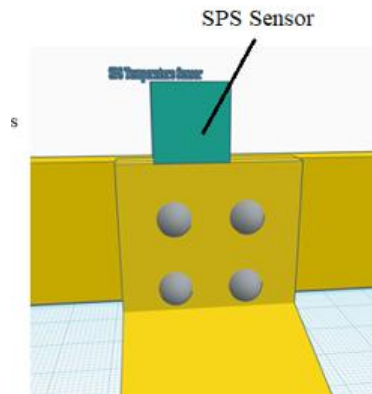


Fig. 11: Zoomed view of busbar joint with sensor

The figures 12 & 13 shows the antenna system mounted over the sensors. The reader antenna shown above emits RF signal towards the SPS sensors. The same RF energy is backscattered by the SPS to send temperature reading to the reader. The reader have to continuously emit RF signal waves to keep the SPS powered-ON during the reading cycle.

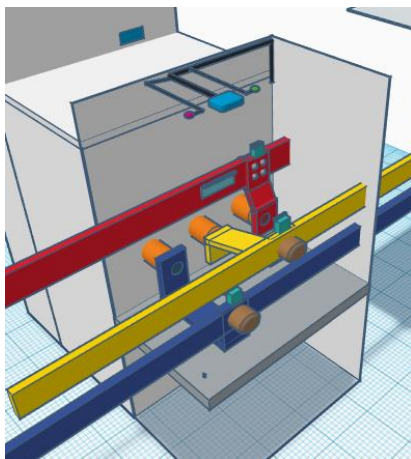


Fig. 12: Antenna system placed over sensors



Fig. 13: Zoomed view of reader antenna and sensor

IV. CONCLUSION

Different modern switchgear failure monitoring technologies were reviewed and compared.

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