ABSTRACT

One of the most important accessories on a transformer is the transformer breather. Breathers help extend the technical life expectancy of the transformer by keeping the moisture inside the transformer at a normal level. Currently, there are two types of breathers available on the market — conventional and self-dehydrating breathers (SDBs). These are also known as smart breathers or maintenance-free breathers. Many asset engineers have realized the technical benefits of the shift from conventional breathers to SDBs; however, the main stumbling block to widespread usage is convincing the commercial team members of the economic benefits gained by installing SDBs.

In this article, an investigation on the return on investment for SDBs is presented, along with the reduction of associated $kgCO_{2e}$ emissions due to the use of SDBs.

KEYWORDS:

cost-benefit, sustainability, return on investment, self-dehydrating breathers

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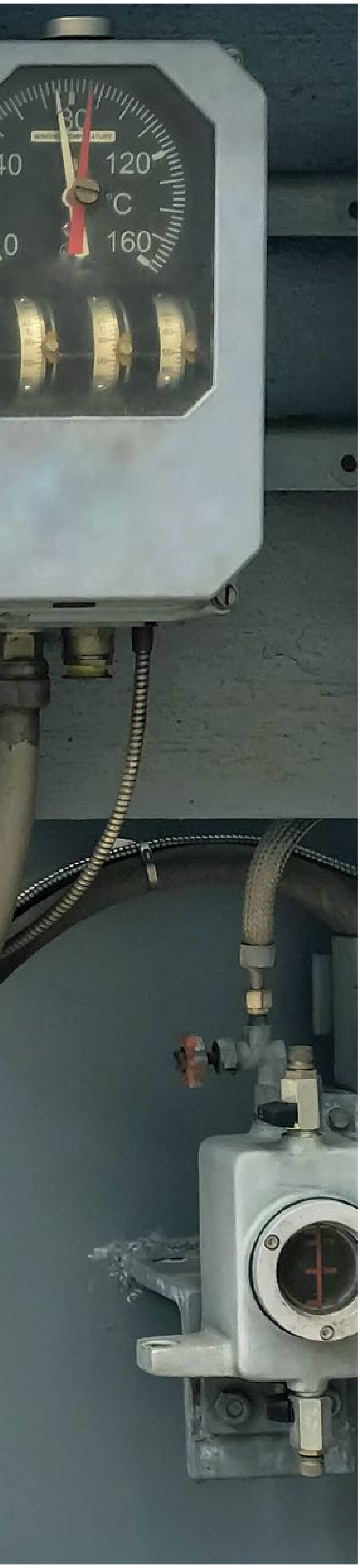

There are many factors that determine the life expectancy of insulation paper, with the most important parameters being temperature, moisture, and oxygen

Sustainable digitalization using self-dehydrating breathers

Introduction

The technical end of life of a transformer depends upon the degradation of its insulation paper. There are many factors that determine the life expectancy of insulation paper, with the most important parameters being temperature, moisture, and oxygen. The moisture in the insulation paper has a significant impact on paper life. IEC 60076-7 [1] demonstrates that the ageing rate of paper insulation increases by 3.66 times at 98 ^{0}C hot spot temperature when the moisture in the paper increases from 0.5 % to 1.5 %, whereas the ageing rate increases by 10.97 times when the moisture in the paper reaches 3.5 %.

To improve the technical end of life of a transformer, the insulating oil must be protected from excess moisture ingress, as there is a dynamic state of equilibrium between the moisture concentration in the oil and the insulation paper. Typically, there are different types of oil preservation systems — free-breathing, membrane-sealed, rubber bladder-sealed, and hermetically sealed systems [2]. The hermetically sealed type offers more moisture protection over the air-breathing type if it is properly sealed from air. Due to certain mechanical limitations of the hermetically sealed type, the majority of power transformers across the world are of a free-breathing type [3]. To protect the oil from direct contact with air moisture, the conservator tank is connected ‘in series’ with the silica gel breather for all the air-breathing type systems. The membrane or rubber bladder placed inside the conservator protects the oil from direct contact with the ambient air, but over time, the material degrades and ruptures; however, this remains undetected due to the difficulty in inspection. Hence, silica gel breather maintenance is extremely crucial, irrespective of the type of the oil preservation system.

The quantity of silica gel required depends on many factors: quantity of oil inside the transformer, average air temperature at the place of installation, average humidity of the environment where the transformer is installed, average thermal cycle of the transformer, and the maintenance interval [4]. The size of the silica gel breather and the quantity of silica gel required is directly proportional to the maintenance interval. The silica gel has a finite capacity to absorb moisture, so it becomes saturated and requires frequent replacement. However, due to unpredictable weather conditions and transformer loading, it is very difficult to predict when the replacement of the silica gel inside the breather is to be performed. For this reason, a coloured indicator (orange or blue) is used with pure silica gel. A completely dry silica gel is ‘orange’ in colour and changes to ‘green’ when saturated with moisture. Hence, silica gel breathers require continuous inspection to track the changes that indicate

> **SDB enables continuous transformer and breather status monitoring and averts the need for frequent replacement, as well as frequent site visits for inspection**

the need for replacement. Sometimes, colour-changing silica gel can be fully saturated internally and show no colour change externally. Thus, it is not always easy to determine whether the silica gel breather provides the required moisture ingress protection. There have been cases where silica gel replacement is not a priority, as everyone is trying to reduce maintenance costs. It is not uncommon for moisture to enter the transformer through a fully saturated traditional breather that is past its maintenance date.

Another less-discussed issue is the end-of-life disposal of silica gel. Silica gel can be regenerated once the colour changes, but typically, it is discarded because it is cheaper to replace than to regenerate. Blue silica gel, which has cobalt chloride, has acute toxic potential for humans [5]. Blue silica gel has high values for acute fish toxicity and acute bacterial toxicity, which become a possibility once it finds its way to a landfill. Blue silica gel tends to be less expensive than orange silica gel while still maintaining the same performance standards; hence, it is still available for use in many countries. In 1998, the European Union prohibited blue silica gel from being sold on European markets. Orange silica gel is not toxic and inert [6]; hence, it is not classified as hazardous waste, but when used in large quantities, it becomes huge additional landfill mass.

This is where the Self Dehydrating Breathers (SDBs) provide an advanced solution — continuous monitoring of the breather status averts the need for frequent replacement, averts frequent site visits for inspection, helps reduce landfill waste, and reduces the total cost of ownership of operating breathers connected to transformers.

Self-dehydrating breather

SDBs have been developed to avoid frequent maintenance and to reactivate the silica gel. Typically, this type of breather has two tanks filled with silica gel. During normal operating conditions, moist air passes through the first tank and silica gel absorbs the moisture. A weight monitoring cell installed inside the tank continuously measures the weight of the silica gel. When the weight of the silica gel exceeds a preset value, a solenoid valve blocks the passage of air through the first tank, and the air is diverted through the second tank. At the same time, a heater inside is activated, and the moisture expelled from the silica gel is removed by an exhaust fan. The heating in the first tank continues until the weight of the silica gel is reduced to the initial value as measured by the weight monitoring cell. When the regeneration of the silica gel is completed, the solenoid valve is de-energized, which stops the airflow through the second tank. The silica gel in the second tank is heated again, and regeneration is initiated. The process goes on cyclically, and the system can work without external intervention. Potential issues to watch out for are electronic board failure, heater failure, solenoid valve failure, weight monitoring cell failure, and drying failure. The typical mean time between failures (MTBF) is around 15 years.

In the next section, the total cost of ownership comparison is carried out for conventional breathers against SDBs.

The total cost of ownership for conventional breathers

In this section, the total cost of ownership for conventional breathers with regard to 66 transformers located at 14 different sites is presented. These transformers are located at an average return distance of 35 km from the transformer service team. The environmental conditions of the transformers' location and typical maintenance interval days are listed in Table 1.

The typical costs of silica gel maintenance for conventional breathers are listed in Table 2. It is to be noted that, if disposal is done ethically, there should be a disposal cost as well.

Based on Table 2, the total cost of ownership for conventional breathers can be calculated (Table 3), assuming the cost of silica gel and labour rate does not change over time: 66 x $300 + $4,042,000 = $4,061,800 over a period of 25 years.

Table 1: Typical environmental conditions

Average ambient temperature (°C)	35
Average humidity (% RH)	65
Average thermal cycle (Δt in °C)	20
Average duration of the thermal cycle (hours)	8
Conventional breather maintenance interval days (days)	90

Table 2: Typical parameters for conventional breathers

Average purchase price of a silica gel breather ($)	$300
Cost of silica gel ($/kg)	20
Labor cost per hour ($)	85
Inspection time per hour per transformer (hours)	0.25
Replacement time per hour per transformer (hours)	1
Visual inspections per year	12
Typical replacement per year (silica gel changes)	4


SDB
DISPLAY PROTECTION
SDB
DISPLAY PROTECTION

Table 3: Total cost of ownership of 66 x conventional breathers in the main tank

Transformer location	Oil quantity (kg)	Quantity of silica gel (kg)	Visual inspection cost per year ($)	Maintenance cost ($)	Total annual cost ($)	Lifetime cost ($)
Site 1 with 8 transformers	17,100	15	$255.00	$1,522.89	$1,777.89	$44,447.22
	17,100	15	$255.00	$1,522.89	$1,777.89	$44,447.22
	29,400	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	25,900	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	25,900	25	$255.00	$2,314.00	$2,569.00	$64,225.00
Site 2 with 3 transformers	24,300	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	24,300	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	24,300	25	$255.00	$2,314.00	$2,569.00	$64,225.00
Site 3 with 4 transformers	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,800	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 4 with 3 transformers	23,800	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,800	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,800	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 5 with 4 transformers	27,400	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 6 with 6 transformers	30,000	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	28,000	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	28,000	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	27,400	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 7 with 3 transformers	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11

Transformer location	Oil quantity (kg)	Quantity of silica gel (kg)	Visual inspection cost per year ($)	Maintenance cost ($)	Total annual cost ($)	Lifetime cost ($)
Site 8 with 4 transformers	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	23,200	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 9 with 5 transformers	31,000	30	$255.00	$2,709.56	$2,964.56	$74,113.89
	31,000	30	$255.00	$2,709.56	$2,964.56	$74,113.89
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 10 with 7 transformers	30,000	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	31,000	30	$255.00	$2,709.56	$2,964.56	$74,113.89
	31,000	30	$255.00	$2,709.56	$2,964.56	$74,113.89
	31,000	30	$255.00	$2,709.56	$2,964.56	$74,113.89
	31,000	30	$255.00	$2,709.56	$2,964.56	$74,113.89
Site 11 with 3 transformers	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 12 with 7 transformers	38,000	35	$255.00	$3,105.11	$3,360.11	$84,002.78
	38,000	35	$255.00	$3,105.11	$3,360.11	$84,002.78
	38,000	35	$255.00	$3,105.11	$3,360.11	$84,002.78
	38,000	35	$255.00	$3,105.11	$3,360.11	$84,002.78
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
Site 13 with 5 transformers	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	23,500	20	$255.00	$1,918.44	$2,173.44	$54,336.11
	38,000	35	$255.00	$3,105.11	$3,360.11	$84,002.78
	38,000	35	$255.00	$3,105.11	$3,360.11	$84,002.78
Site 14 with 4 transformers	17,100	15	$255.00	$1,522.89	$1,777.89	$44,447.22
	17,100	15	$255.00	$1,522.89	$1,777.89	$44,447.22
	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00
	27,500	25	$255.00	$2,314.00	$2,569.00	$64,225.00

> **Due to unpredictable weather conditions and transformer loading, it is very difficult to predict when the replacement of the silica gel inside the breather is to be performed**

The total cost of ownership for self-dehydrating breathers

The assumed increase in the purchase price for one SDB is 6 x $ of conventional breathers. The typical parameters for SDBs are listed in Table 4.

Based on the data from Table 4, the total cost of ownership for conventional breathers can be calculated as:

- Initial purchase price =
  66 x $3000 = $198,000
- Mid-life purchase price =
  66 x $3000 = $198,000
- Total maintenance, including mid-life replacement = $40,675 (one site inspection visit every year for 25 years + one replacement in 25 years)
- Total cost of ownership = $436,675

Total cost of ownership comparison

The total cost of ownership comparison is provided in Table 5. It is evident that SDBs provide a significant reduction in the lifetime total cost of ownership.

In the last few decades, climate change and global warming have emerged as important environmental issues in addition to cost savings. The cause of global warming is the increase in greenhouse gas emissions (GHG). Greenhouse gases are expressed in mass-based CO_2 equivalents (CO_{2e}), which is the unit of measurement from the ISO 14067:2018 standard [7]. The objective of considering CO_{2e} emissions is to reduce the use of natural resources and emissions into the environment, as well as to improve social performance at different stages of the transformer's life cycle. In the next section, two such parameters are calculated — CO_{2e} emissions due to silica gel quantity and CO_{2e} emissions due to site visits for breather inspection.

CO_{2e} emissions due to silica gel quantity

Based on Table 3, the total amount of silica gel in conventional breathers for all of the 66 different transformers = 1550 kg. In this example, the silica gel is replaced four times annually = 6200 kg. Over a period of 25 years, the total amount of silica gel required would be 155 tons. The primary environmental issue with silica gel is the way it is manufactured — it is chemical, water, and energy-hungry and produces wastewater. One ton of silica requires 0.66 tons of H_2SO_4, 3.90 tons of water glass (as a source of aqueous alkali metal solution) and 40 m^3 of water. About 15–24 GJ is consumed for the same amount of silica [8]. Other than the energy required for production, treating the waste that comes out at various stages of production can be energy demanding as well. The global warming potential (GWP) is estimated to be between 3.48–4.12 (kg CO_{2e}/kg) [8]. Using this value, the GWP reduction associated with silica gel quantity is calculated in Table 6.

The quantity of silica gel required depends on the following factors: the quantity of oil inside the transformer, the average air temperature at the place of installation, the average humidity of the environment where the transformer is installed, the average thermal cycle of the transformer, the average duration of the thermal cycle, and maintenance interval in days. While the environmental conditions are the same for both types of breathers, the quantity of silica gel required is significantly reduced in the SDB, as the typical maintenance interval is automated, unlike with the conventional breather, i.e., days or weeks compared to months.

CO_{2e} emissions due to site inspection

For a typical petrol vehicle between 1600–2000 cc, the GWP is calculated at 0.22 kgCO_{2e}/km [9]. With the travel distance listed in Table 7 below, the total CO_{2e} emissions due to silica gel inspection for 25 years is 32,604 kgCO_{2e}. With the frequency of inspection reduced to 1 x inspection visit per year due to SDBs, the CO_{2e} emissions can be reduced to 2,707 kgCO_{2e}, i.e., reduction by 92 %!

> **The use of SDBs is also beneficial in terms of CO_{2e} emissions and has a positive ecological impact**

Table 4: Typical parameters for SDBs

Average purchase price of a digital aggregator + SDB ($)	$3000
Labour cost per hour ($)	85
Inspection time per hour per transformer (hours)	0.25
Replacement time per hour per transformer (hours)	1
Visual inspections per year	1
Typical MTBF of SDB (years)	15 i.e., 2 units of SDB over 25 years

Table 5: Lifetime TCO comparison (25 years)

Conventional breathers TCO = $4,061,800	SDBs TCO = $436,675	Savings $3,625,125

Table 6: Global warming potential due to silica gel quantity

Conventional breathers Total lifetime silica gel used in 66 transformers ~ 155 tons GWP (silica gel) ~ 539–638 tons CO_{2e}	SDBs Total amount of silica gel in 66 different transformers = 165 kg. Over 25 years, the total amount of silica gel would be 330 kg. GWP (silica gel) ~ 1.14–1.36 tons CO_{2e}	Reduction in GHG emissions > 500 tons if conventional breathers are replaced with SDBs

Table 7: Global warming potential due to site inspection visits

Transformer location	Frequency of inspections per year	Return distance travelled (km)	GWP due to site visits per year	CO_{2e} emissions due to site visits for 25 years
Site 1 with 8 transformers	12	40	105.6 kgCO_{2e}	2640 kgCO_{2e}
Site 2 with 3 transformers	12	30	79.2 kgCO_{2e}	1980 kgCO_{2e}
Site 3 with 4 transformers	12	30	79.2 kgCO_{2e}	1980 kgCO_{2e}
Site 4 with 3 transformers	12	16	42.2 kgCO_{2e}	1056 kgCO_{2e}
Site 5 with 4 transformers	12	20	52.8 kgCO_{2e}	1320 kgCO_{2e}
Site 6 with 6 transformers	12	20	52.8 kgCO_{2e}	1320 kgCO_{2e}
Site 7 with 3 transformers	12	24	63.6 kgCO_{2e}	1584 kgCO_{2e}
Site 8 with 4 transformers	12	30	79.2 kgCO_{2e}	1980 kgCO_{2e}
Site 9 with 5 transformers	12	26	68.8 kgCO_{2e}	1716 kgCO_{2e}
Site 10 with 7 transformers	12	36	95.04 kgCO_{2e}	2376 kgCO_{2e}
Site 11 with 3 transformers	12	70	184.87 kgCO_{2e}	4620 kgCO_{2e}
Site 12 with 7 transformers	12	66	174.2 kgCO_{2e}	4356 kgCO_{2e}
Site 13 with 5 transformers	12	66	174.2 kgCO_{2e}	4356 kgCO_{2e}
Site 14 with 4 transformers	12	20	52.8 kgCO_{2e}	1320 kgCO_{2e}
Total				32,604 kgCO_{2e}

> **The use SDBs is an excellent example of sustainable digitalization, as it helps, supports, and enables the twin transition to a low-carbon power grid: digital and sustainable**

Conclusion

Conventional breathers require regular inspection and maintenance, and if not performed regularly, ingress of moisture in the oil preservation system becomes a reality. This causes accelerated ageing of the paper insulation system and significantly decreases the technical end of transformer life. Regular inspection and maintenance is not only a recurring cost but also has environmental concerns associated with it — CO_{2e} emissions due to silica gel quantity used in transformers, CO_{2e} emissions due to site inspection visits, and regular addition of saturated silica gel to the landfill. SDBs, on the other hand, do not require regular inspection and maintenance during their typical MTBF period of 15 years. This leads to lower CO_{2e} emissions due to site inspection visits. The quantity of silica gel used is significantly lower, as it is auto-regenerated, which, again, leads to lower CO_{2e} emissions due to silica gel quantity and lower mass added to the landfill. The total cost of ownership for SDBs is significantly lower than the total cost of ownership of conventional breathers, with a payback period typically shorter than 3 years. A sensitivity analysis of the calculations presented in this article is recommended to accommodate local environmental variations and maintenance practices.

The use SDBs, smart breathers or maintenance-free breathers is an excellent example of sustainable digitalization. It helps, supports and enables the twin transition to a low-carbon power grid with digitalization supporting sustainability.

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