# Comparative Study of Solid, Liquid, and Gaseous Insulation on the Distribution Transformer

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**Abstract**

*Distribution transformers are critical for reliable power delivery, with insulation failure being a leading cause of outages worldwide. Bhutans diverse climatic conditions ranging from humid subtropical valleys to cold high-altitude regions place unique stresses on transformer insulation through moisture ingress, thermal cycling, and pollution. This paper presents a comparative evaluation of solid, liquid, and gaseous insulation systems based on dielectric strength, ageing resistance, moisture tolerance, environmental footprint, and lifecycle/maintenance considerations. Data synthesis from IEC 60071/60076 standards, experimental studies, and industry reports indicates that natural esters outperform mineral oils with superior ageing resistance and 3040% higher moisture tolerance, while maintaining comparable dielectric strength. SF6 remains unmatched in dielectric strength and arc-quenching ability but is limited by its extremely high global warming potential (23,500Œ CO2). Solid epoxy resins provide robust dielectric behavior in dry climates but are sensitive to thermal cycling and humidity stress, though nano-composite epoxies show improved resilience. Regional suitability analysis highlights natural esters for Bhutans humid southern regions solid epoxy for cold northern areas, and hybrid esterepoxy systems for mixed climates. The findings demonstrate ester-based retrofilling and hybrid insulation approaches as practical, sustainable pathways for enhancing transformer reliability and reducing environmental impact in Bhutan*

***Keywords***— Distribution transformers, insulation systems, natural ester, SF6 alternatives, dielectric properties, ageing, moisture tolerance, epoxy, Bhutan.

## 1 Introduction

Distribution transformers are essential in delivering medium-voltage (MV) power to low-voltage networks, yet insulation failure remains one of the main causes of outages and costly maintenance worldwide [1]-[3]. Bhutans varied climate from humid subtropical valleys in the south to freezing northern highlands and mixed seasonal conditions in central and eastern regions exposes insulation systems to moisture, pollution, and thermal cycling stresses that accelerate hydrolysis, ageing, and dielectric breakdown [4],[5]. These localized challenges demand a region-specific evaluation of insulation systems that balances technical reliability, lifecycle costs, and environmental sustainability.

Figure 1: Oil-insulated 500 KVA Distribution Transformer in JNEC

## 2 Literature Review

Conventional mineral oil has long been used for its low cost and strong dielectric strength, but its flammability, lack of biodegradability, and poor performance under moisture stress limit its long-term suitability [6],[7]. Natural esters, by contrast, offer higher flash points, stronger moisture absorption, and improved ageing performance while being biodegradable [8],[9]. Synthetic esters provide stability across climates though with lower biodegradability [8]. For gaseous insulation, SF6 remains unmatched in dielectric strength and arc-quenching properties [10], but its global warming potential (23,500Œ CO2) makes it environmentally unsustainable, motivating alternatives such as fluoronitrileCO2 blends, dry air, and N2 [11],[12]. Solid epoxy resins, widely applied in dry-type transformers, provide robust dielectric performance but degrade under thermal cycling and humidity, while nano-composite epoxies offer improved resistance to tracking and partial discharges [13],[14]. Against this background, the present study compares solid, liquid, and gaseous insulation systems using IEC standards, experimental data, and literature across five criteria: dielectric strength, ageing resistance, moisture tolerance, environmental footprint, and lifecycle/maintenance requirements, with special focus on natural esters, SF6, epoxy systems, and hybrid approaches tailored to Bhutans climatic zones.

## 3 Methodology

This study employs a comparative performance framework with five evaluation axes: dielectric strength, ageing resistance, moisture tolerance, environmental footprint, and lifecycle/maintenance.

Data sources include IEC 60243/60071/60076 standards, experimental studies, and industry reports [4], [6],[7],[12].

### 3.1 Performance Index Normalization

Each insulation type was normalized to a 0-10 index:

$$P_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \times 10 \quad (1)$$

Where, Pi is the normalized performance score, Xi is the raw parameter value, and Xmax, Xmin are the upper and lower bounds across materials. This ensures comparability across diverse metrics such as dielectric strength and moisture uptake.

### 3.2 Dielectric Strength

Dielectric performance was obtained from IEC 60243 test data and reported laboratory results. For gaseous systems, lightning impulse breakdown strength of SF6 and its alternatives were included [10].

### 3.3 Ageing Resistance

Ageing was assessed using degree of polymerization (DP) of cellulose after accelerated thermal ageing [2]. Higher retained DP indicates slower degradation.

### 3.4 Moisture Tolerance

Moisture tolerance was quantified using water saturation limits and breakdown strength under wet conditions. Natural esters saturation capacity (1000 ppm) far exceeds that of mineral oils (3560 ppm), reducing bubble formation during overload [6],[8].

### 3.5 Environmental Footprint

Environmental impact was measured via global warming potential (GWP) for gases and biodegradability for liquids [11]. SF6 received the lowest score due to its GWP of 23,500 X CO2.

### 3.6 Lifecycle and Maintenance

Lifecycle assessment incorporated retrofilling potential, operational reliability, and ease of field handling. Reports on ester retrofilling and epoxy-based dry transformers were included [7],[9],[13].

### 3.7 Comparative Table

Table 1: Comparative Performance of Insulation Types

| **Insulation Type** | **DS** | **AR** | **MT** | **EF** | **LC** |
|---|---|---|---|---|---|
| Mineral Oil | 7 | 5 | 4 | 3 | 6 |
| Natural Esters | 8 | 8 | 9 | 7 | 8 |
| Synthetic Esters | 8 | 7 | 8 | 6 | 7 |
| $SF_6$ Gas | 10 | 9 | 10 | 1 | 9 |
| Solid Epoxy | 9 | 7 | 6 | 6 | 7 |

# 4 Results and Discussion

The comparative analysis demonstrates clear trade-offs among liquid, solid, and gaseous insulation systems. Table 1 presents normalized performance indices across five criteria. To enhance visualization, a radar chart is recommended, highlighting how ester-based fluids outperform mineral oils in moisture tolerance and ageing resistance, while SF6 dominates dielectric strength but fails environmentally [6],[8],[10].

## 4.1 Liquid Insulation

Natural esters scored highest in moisture tolerance (9/10) and ageing resistance (8/10), with dielectric strength comparable to mineral oil. Their high water saturation ($\sim$ 1000 ppm) reduces bubble formation risk during overloads, unlike mineral oils ($\sim$ 35–60 ppm) [6],[8]. Synthetic esters provide balanced performance across climates, though with reduced biodegradability.

Figure 2: Natural Ester Insulated Transformer

## 4.2 Gaseous Insulation

SF6 achieved the highest dielectric strength (10/10) and moisture tolerance but scored lowest (1/10) in environmental footprint due to its extremely high GWP (23,500 Œ CO2) [10],[11]. Alternatives such as fluoronitrileCO2 blends and dry air mixtures show promise but require further field validation [12].

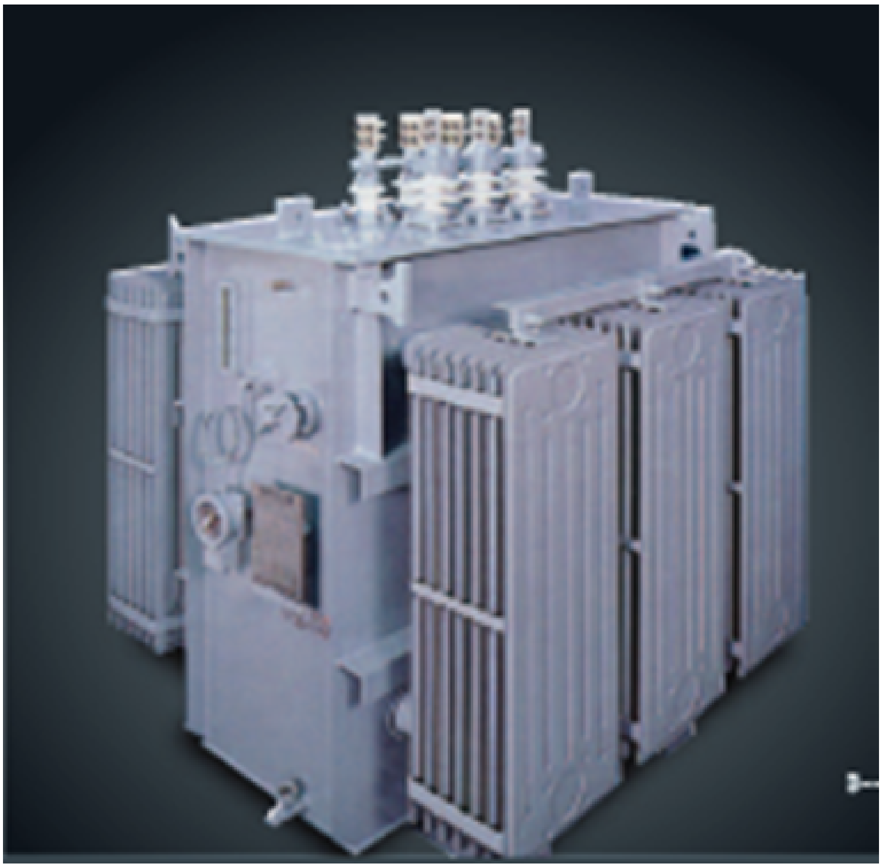

Figure 3: Natural SF6 Gas Insulated Transformer

## 4.3 Solid Insulation

Solid epoxy resins demonstrated strong dielectric strength (1520 kV/mm) but suffered under cyclic humidity and thermal stresses [13]. Nano-composite epoxies improved resistance to tracking and partial discharges by up to 20%, making them more suitable for harsh conditions [14].

Figure 4: Natural SF6 Gas Insulated Transformer

### 4.4 Regional Suitability for Bhutan

A region-specific assessment indicates:

- Southern Bhutan (humid, monsoon climate): Natural esters recommended.
- Northern Bhutan (cold, high altitude): Solid epoxy with thermal management preferred.
- Eastern Bhutan (seasonal humidity): Synthetic esters or esterepoxy hybrids.
- Western Bhutan (cool valleys): Natural esters preferable; mineral oil acceptable with derating.
- Central Bhutan (mixed wetdry): Hybrid esterepoxy systems recommended.

### 4.5 Regional Suitability for Bhutan

Table 2: Regional Suitability Comparison

| Region | NE | SE | MO | Epoxy |
|---|---|---|---|---|
| South | 9 | 6 | 4 | 5 |
| East | 7 | 8 | 5 | 7 |
| West | 8 | 6 | 6 | 6 |
| Central | 8 | 7 | 5 | 8 |
| North | 5 | 6 | 3 | 9 |

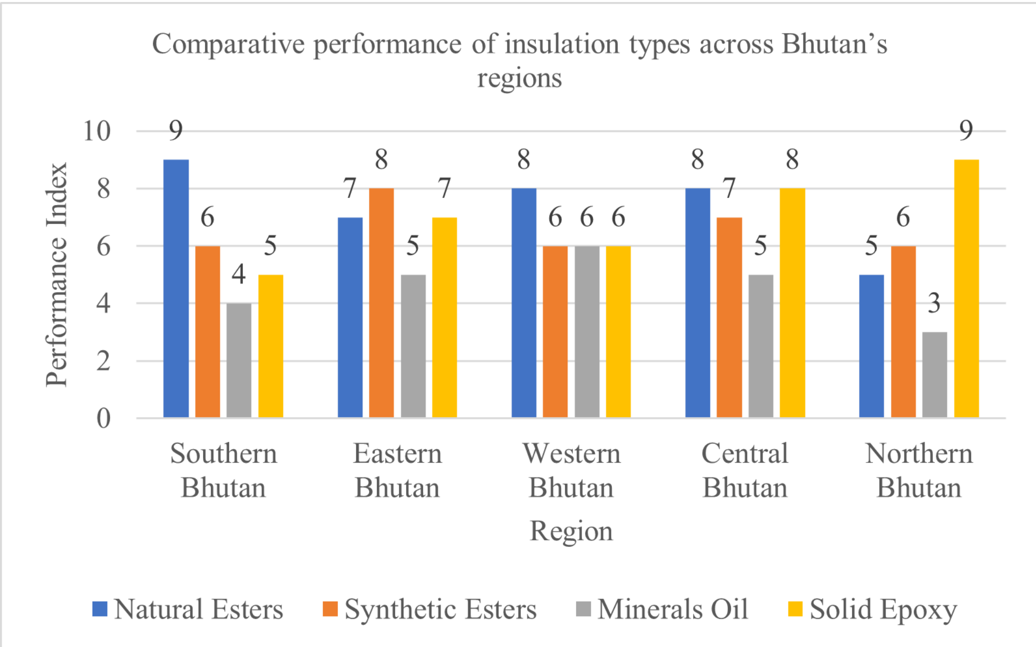


Figure 5: Comparative performance of insulation types across Bhutans regions

## 5 Conclusion

This study presented a comparative evaluation of solid, liquid, and gaseous insulation systems for distribution transformers under Bhutans diverse climatic conditions. Results show that natural esters provide the most balanced performance, offering superior ageing resistance, high moisture tolerance, and strong biodegradability compared to mineral oils [6]-[9]. SF6 remains unmatched in dielectric strength and arc-quenching properties but its exceptionally high global warming potential (23,500 Œ CO2) makes it environmentally unsustainable [10]-[12]. Solid epoxy exhibits robust dielectric performance in dry and stable environments but is vulnerable to thermalhumidity stresses; Nano-composite epoxy variants show improved resilience [13],[14].

Regional suitability analysis suggests natural esters are best for humid southern Bhutan, solid epoxy for cold northern zones, esterepoxy hybrids for central and eastern regions, and natural esters with possible mineral oil use (with derating) in the west.

For Bhutanese utilities, practical steps include retrofilling existing mineral-oil transformers with esters, deploying hybrid esterepoxy insulation in mixed climates, and reducing reliance on SF6 through exploration of eco-efficient alternatives.

# 6 Recommendation

Future work should include;

- Field trials of ester-based retrofills across Bhutans climatic zones.
- Long-term monitoring using degree of polymerization (DP), furan analysis, and dissolved gas analysis (DGA).
- Pilot testing of SF6 alternatives such as fluoronitrile mixtures.
- Development of Nano-composite epoxy formulations for extended solid insulation lifespan.

  By adopting these measures, Bhutan can move toward a more reliable, climate-adapted, and environmentally sustainable distribution transformer fleet.

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# References

[1] P. Jusner, E. Schwaiger, A. Potthast, and T. Rosenau, *Thermal stability of cellulose insulation in electrical power transformers A review*, Carbohydrate Polymers, vol. 252, p. 117196, 2021.

[2] D. Feng, J. Hao, R. Liao, X. Chen, L. Cheng, and M. Liu, *Comparative study on the thermal-aging characteristics of cellulose insulation polymer immersed in new three-element mixed oil and mineral oil*, Polymers, vol. 11, no. 8, p. 1292, 2019.

[3] K. Lam, *A tale of two esters Why the natural one is the better dielectric fluid*, Cargill Bioindustrial White Paper, 2022.

[4] J. Benitez, *IEC 60071-1:2011 Insulation coordination definitions, principles & rules*, Studocu, 2024.

[5] IEC/IEEE, *IEC/IEEE 60076-16:2018 Power transformers*, International Electrotechnical Commission, 2018.

[6] A. Ghazzaly, L. Nasrat, K. Ebnalwaled, and M. Rihan, *Recent advances in strengthening electrical, mechanical and thermal properties of epoxy-based insulators for electrical applications*, SVU-International Journal of Engineering Sciences and Applications, vol. 5, no. 2, pp. 153–161, 2024.

[7] R. Liao, J. Hao, G. Chen, Z. Ma, and L. Yang, *A comparative study of physicochemical, dielectric and thermal properties of pressboard insulation impregnated with natural ester and mineral oil*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 18, no. 5, pp. 1626–1637, 2011.

[8] J.-S. An, S.-H. Choi, J.-J. Bang, J.-I. Jung, and C.-S. Huh, *Analysis of accelerated aging natural ester oil and mineral oil in distribution transformers*, Transactions of the Korean Institute of Electrical Engineers, vol. 60, no. 6, pp. 1163–1168, 2011.

[9] S. Tenbohlen and M. Koch, *Aging performance and moisture solubility of vegetable oils for power transformers*, IEEE Transactions on Power Delivery, vol. 25, no. 2, pp. 825–830, 2010.

[10] Y. Qiu, Y. F. Liu, A. Sun, and E. Kuffel, *Dielectric strengths of $SF_6/N_2$ and $SF_6/CO_2$ gas mixtures at low pressure-gap separation values*, Journal of Physics D: Applied Physics, vol. 21, no. 1, pp. 208–209, 1988.

[11] K. Bandara, C. Ekanayake, T. Saha, and H. Ma, *Performance of natural ester as a transformer oil in moisture-rich environments*, Energies, vol. 9, no. 4, p. 258, 2016.

[12] C. Méndez, A. K. Koseoglu, C. Olmo, C. J. Renedo, and A. Ortiz, *Comparative thermal ageing analysis of ester dielectric fluids impregnating TUK paper: Implications for transformer maintenance standards*, Applied Sciences, vol. 15, no. 21, p. 11517, 2025.

[13] P. Parvizi, M. Jalilian, and K. D. Dearn, *Epoxy composites reinforced with nanomaterials and fibres: Manufacturing, properties, and applications*, Polymer Testing, vol. 146, p. 108761, 2025.

[14] D. Liu *et al.*, *Research on the thermal aging characteristics of cured epoxy resin insulating materials for DC bushings*, Polymers, vol. 17, no. 8, p. 1064, 2025.