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Towards a Greener Grid: Modelling the role of Ester Oil in Sustainable Transformer Operation

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Abstract - As the demand for cleaner and more sustainable power systems grows, the use of eco-friendly transformer oils is gaining attention. This study explores ester oil, a plant-based and biodegradable alternative to traditional mineral oil, and evaluates its suitability for transformer insulation. Using MATLAB simulations, the performance of both oils was analyzed in terms of transformer aging, fire safety, environmental impact, cost over time, and response to load changes. The results show that ester oil not only withstands higher temperatures and slows down aging but also significantly lowers the risk of fire due to its higher flash point. In terms of sustainability, ester oil reduces carbon emissions and environmental hazards in case of leaks. Though the initial investment is slightly higher, its reduced maintenance needs and easier disposal make it cost-effective in the long run. The findings suggest that ester oil can play a crucial role in modernizing the grid with safer, greener technology that meets long-term environmental and performance goals.

***Key Words*:** Ester oil, mineral oil, transformer aging, environmental sustainability, fire safety, lifecycle cost

1.INTRODUCTION

In today's world, where energy demands are soaring and environmental concerns are intensifying, the shift towards greener and more sustainable technologies is no longer optional—it's essential. Within the power distribution sector, transformers play a vital role in maintaining the efficiency and stability of electrical networks. Traditionally, mineral oil has been the preferred insulating and cooling medium in transformers due to its availability and proven performance. However, its environmental drawbacks, including poor biodegradability and the risk of soil and water contamination in case of leaks, have prompted researchers and industries to explore safer alternatives.

Ester oil, a natural and biodegradable fluid derived from plant-based sources, has emerged as a promising substitute. Apart from being environmentally benign, ester oil offers advantages like higher thermal stability, better moisture tolerance, and improved fire safety due to its high flash point. These properties not only enhance transformer performance under demanding conditions but also contribute to reducing long-term operational costs and ecological risks.

This paper aims to evaluate the technical and economic feasibility of replacing mineral oil with ester oil in transformers. Through MATLAB simulations, the study investigates transformer aging, thermal behavior, environmental impact, fire risk, and lifecycle cost under both oil types. The goal is to support informed decision-making in favor of sustainable grid infrastructure.

2.1 Comparative Properties of Ester Oil and Mineral Oil

- **Source and Sustainability**

Ester oil is obtained from natural, plant-based materials, making it biodegradable and environmentally friendly. In contrast, mineral oil is derived from fossil fuels and poses a greater risk to the environment in case of spills or leaks.

- **Thermal Performance**

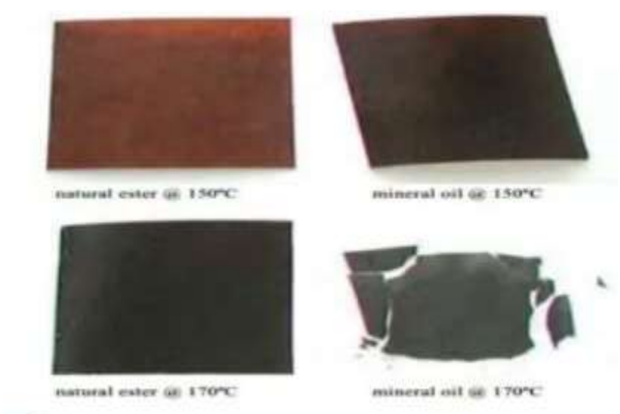

Fig 1: Insulation Aging Behavior in Ester Oil vs Mineral Oil Environments

Ester oil can handle higher temperatures due to better thermal conductivity, which allows transformers to operate efficiently under varying loads. Mineral oil, however, tends to degrade faster when exposed to high temperatures over time.

- **Moisture Absorption**

Ester oil performs well even in the presence of moisture, maintaining its insulating strength. Mineral oil, on the other hand, is more vulnerable to moisture, which can significantly reduce its dielectric performance.

- **Oxidation Resistance**

One of the benefits of ester oil is its strong resistance to oxidation. This helps reduce sludge formation and extends the oil's usable life. Mineral oil is more prone to oxidation, which can lead to internal contamination and frequent maintenance.

- **Fire Safety**

With a flash point of around 300°C, ester oil is much safer in high-temperature environments. This makes it suitable for use in areas where fire safety is a concern. Mineral oil has a lower flash point, increasing the likelihood of fire during faults.

- **Environmental Impact**

In the event of leakage, ester oil breaks down naturally and poses minimal harm to soil or water. Mineral oil is not biodegradable and can cause long-term environmental damage if not handled properly.

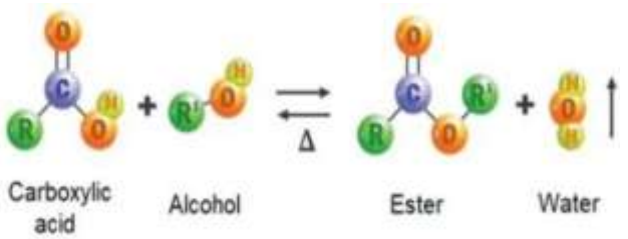

Fig 2:

Environmental sustainability profile of ester oil

- **Cost and Long-Term Value**

Although ester oil costs more at the time of purchase, it often proves more economical over the transformer's life. This is due to its durability, lower maintenance needs, and cheaper disposal. Mineral oil may seem budget-friendly upfront but can result in higher recurring costs.

2.2 Key Benefits of Ester Oil:

- **Renewable and Biodegradable**:

Environmental Impact: Ester oils are derived from renewable plant-based sources, making them biodegradable and significantly less harmful to the environment in the event of spills or leaks. Unlike mineral oils, ester oils break down naturally over time, reducing soil and water contamination and aligning with environmental safety standards.
Sustainability: Using a biodegradable, carbon-neutral fluid like ester oil contributes to reducing the grid's ecological footprint and supports environmental stewardship goals

- **Enhanced Transformer Performance and Longevity**:

Thermal Stability: Ester oil has a higher thermal conductivity and can operate at higher temperatures than mineral oil. This property allows transformers to handle more stress and fluctuations in load, which is increasingly common in renewable energy grids.
Aging and Maintenance: Because ester oils are more resistant to oxidation and moisture absorption, transformers filled with ester oil tend to have a slower aging process. This reduces maintenance requirements and extends transformer life, yielding long-term reliability and cost savings.

- **Improved Fire Safety**:

High Flash Point: Ester oils have a much higher flash and fire point than mineral oils, making them far safer in high-temperature environments and reducing the risk of transformer fires. This fire-resistant quality lowers insurance and risk management costs and increases the feasibility of installing transformers in urban, densely populated, or environmentally sensitive areas.

Reduced Fire-related Emissions: The high fire point reduces the likelihood of fire-related emissions and pollution, contributing to a cleaner and safer operational environment.

- **Lifecycle Cost Benefits**:

Reduced Maintenance and Disposal Costs: Although ester oil can be more expensive initially, its extended service life and reduced need for replacement provide substantial lifecycle cost savings. Ester oils also avoid costly hazardous waste disposal processes required for mineral oils, further reducing the overall operational cost.

Support for Sustainable Asset Management: The longer life and reduced maintenance needs of ester oil-filled transformers support the principles of sustainable asset management, lowering replacement frequencies and minimizing the environmental impacts of new material production

- **Alignment with Carbon Reduction Goals:**

Carbon-Neutral Properties: Being derived from plants, ester oils are carbon-neutral over their lifecycle, as the plants absorb CO_2 during growth. This makes ester oil a strategic choice for utilities looking to lower their carbon footprint in alignment with climate goals and regulatory requirements.

Reduced Emissions Across the Supply Chain: Ester oil's sustainability extends beyond its use in transformers, supporting carbon reduction in the production, maintenance, and disposal stages. Using ester oils contributes to the broader goal of reducing emissions across the electricity grid's entire supply chain.

2.3 Simulation-Based Performance Analysis of Transformers: A Comparison of Ester and Mineral Oils Using MATLAB

1.Aging Simulation

Transformer aging can be modeled by simulating how temperature and oxidation affect the dielectric strength and viscosity of the oil over time.

MATLAB CODE

Step-1

```
% Properties for Ester Oil ester_oil.thermal_conductivity = 0.15; % W/(m·K) ester_oil.viscosity = 0.05; % Pa·s ester_oil.dielectric_strength = 50; % kV/mm ester_oil.density = 920; % kg/m^3 ester_oil.specific_heat = 1900; % J/(kg·K)
% Properties for Mineral Oil mineral_oil.thermal_conductivity = 0.12; % W/(m·K) mineral_oil.viscosity = 0.08; % Pa·s mineral_oil.dielectric_strength = 30; % kV/mm mineral_oil.density = 870; % kg/m^3 mineral_oil.specific_heat = 1800; % J/(kg·K)
```

Step-2

```
% Constants for Arrhenius equation
Ea = 10000; % Activation energy (J/mol) R = 8.314; % Gas constant (J/(mol·K))
initial_temperature = 300; % Initial operating temperature in Kelvin
% Time vector for simulation
time_hours = 0:100:10000; % in hours
% Calculate Aging Factor over time
aging_factor_ester = exp(Ea ./ (R * (initial_temperature + 0.5 * time_hours/100))); aging_factor_mineral = exp(Ea ./ (R * (initial_temperature + 0.75 * time_hours/100)));
% Adjust dielectric strength based on aging
dielectric_strength_ester = ester_oil.dielectric_strength ./ aging_factor_ester;
dielectric_strength_mineral = mineral_oil.dielectric_strength ./ aging_factor_mineral;
% Plot dielectric strength over time figure;
plot(time_hours, dielectric_strength_ester, 'r', time_hours, dielectric_strength_mineral, 'b'); xlabel('Time (hours)');
ylabel('Dielectric Strength (kV/mm)');
```

legend('Ester Oil', 'Mineral Oil'); title('Dielectric
Strength Degradation Over Time');

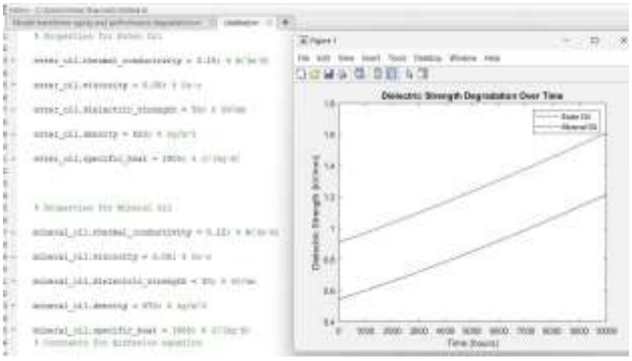

Fig 3 : Dielectric Strength degradation over time (Ester vs Mineral Oil)

2. Environmental Sustainability Impact

The environmental benefits of ester oil over mineral oil can be represented by a model of CO_2 emissions reduction and biodegradability. Define an emissions factor for both oils and simulate cumulative environmental impact over the transformer's lifecycle.

MATLAB CODE

% Emissions factor (arbitrary units for illustration) emission_factor_ester = 0.5; % Lower CO2 emissions due to biodegradability emission_factor_mineral = 1.5; % Higher CO2 emissions for mineral oil

% Biodegradability impact (arbitrary units) biodegradability_ester = 0.2; % Lower environmental impact due to biodegradability biodegradability_mineral = 0.8; % Higher environmental impact

% Calculate cumulative environmental impact cumulative_impact_ester = emission_factor_ester * time_hours * biodegradability_ester; cumulative_impact_mineral = emission_factor_mineral * time_hours * biodegradability_mineral;

% Plot environmental impact over time figure; plot(time_hours, cumulative_impact_ester, 'g', time_hours, cumulative_impact_mineral, 'm'); xlabel('Time (hours)'); ylabel('Cumulative Environmental Impact (arbitrary units)'); legend('Ester Oil', 'Mineral Oil'); title('Environmental Impact Comparison Over Transformer Lifecycle');

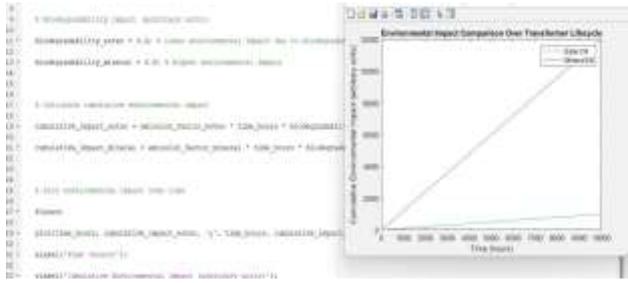

Fig 4: Environment Impact (Ester vs Mineral oil)

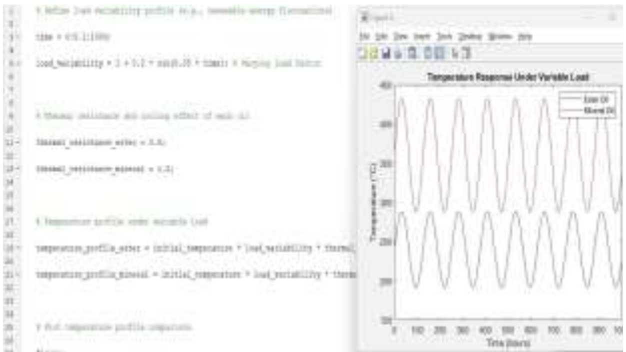

Fig 6: Temperature Simulation under variable load (Ester vs Mineral)

3.Safety and Fire risk analysis:

Simulated the safety benefits of ester oils due to their higher flash point. This simulation models the probability of fire incidents over time

MATLAB CODE:

% Fire risk parameters
fire_risk_factor_ester = 0.05; % Lower risk due to high flash point fire_risk_factor_mineral = 0.2; % Higher risk due to low flash point
% Probability of fire incidents over time (arbitrary model) fire_risk_ester = fire_risk_factor_ester * time_hours / 10000; fire_risk_mineral = fire_risk_factor_mineral * time_hours / 10000;
% Plot fire risk over time figure; plot(time_hours, fire_risk_ester, 'c', time_hours, fire_risk_mineral, 'k'); xlabel ('Time (hours)');

ylabel('Probability of Fire Incident'); legend('Ester Oil', 'Mineral Oil'); title('Fire Risk Comparison Over Time');

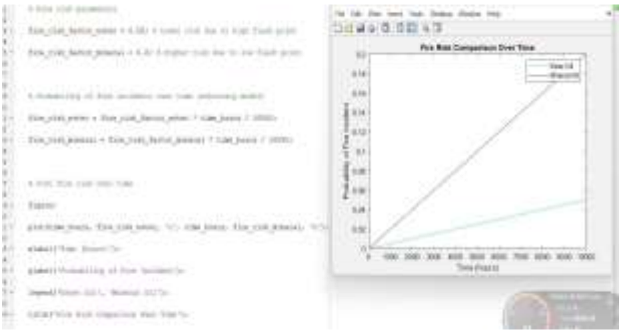

Fig 5: Fire Risk Analysis of ester and mineral oil

4. Performance Simulation Under Variable Loads

Ester oils are known to perform well under variable loads, which is typical in renewable energy grids. Here's how to simulate the performance under load variability.

MATLAB CODE:

% Define load variability profile (e.g., renewable energy fluctuations) time = 0:0.1:1000;
load_variability = 1 + 0.2 * sin(0.05 * time); % Varying load factor

% Thermal resistance and cooling effect of each oil thermal_resistance_ester = 0.8;
thermal_resistance_mineral = 1.2;

% Temperature profile under variable load
temperature_profile_ester = initial_temperature * load_variability * thermal_resistance_ester;

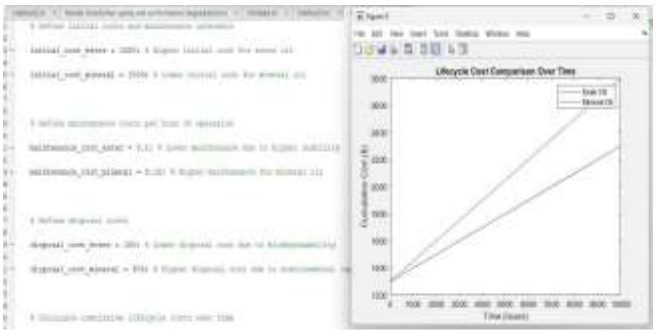

Fig 7: Lifecycle cost comparison Over time (Ester vs Mineral oil)

temperature_profile_mineral = initial_temperature * load_variability * thermal_resistance_mineral;

% Plot temperature profile comparison figure;
plot(time, temperature_profile_ester, 'b', time, temperature_profile_mineral, 'r');
xlabel('Time (hours)'); ylabel('Temperature (°C)'); legend('Ester Oil', 'Mineral Oil');
title('Temperature Response Under Variable Load');

5. Lifecycle Cost Analysis:

Compared the lifecycle costs of ester oil and mineral oil by simulating initial investment, maintenance, and disposal costs

MATLAB CODE:

% Define initial costs and maintenance intervals initial_cost_ester = 1200; % Higher initial cost for ester oil initial_cost_mineral = 1000; % Lower initial cost for mineral oil

% Define maintenance costs per hour of operation
maintenance_cost_ester = 0.1; % Lower maintenance due to higher stability maintenance_cost_mineral = 0.15; % Higher maintenance for mineral oil

% Define disposal costs
disposal_cost_ester = 100; % Lower disposal cost due to biodegradability disposal_cost_mineral = 300; % Higher disposal cost due to environmental impact

% Calculate cumulative lifecycle costs over time
cumulative_cost_ester = initial_cost_ester + time_hours * maintenance_cost_ester + disposal_cost_ester;

cumulative_cost_mineral = initial_cost_mineral + time_hours * maintenance_cost_mineral + disposal_cost_mineral;

% Plot lifecycle cost comparison figure;
plot(time_hours, cumulative_cost_ester, 'b', time_hours, cumulative_cost_mineral, 'r'); xlabel('Time (hours)');
ylabel('Cumulative Cost ($)'); legend('Ester Oil', 'Mineral Oil');
title('Lifecycle Cost Comparison Over Time');

2.4 Challenges of Ester Oil

Higher Initial Cost:
Ester oil is more expensive to procure compared to mineral oil, which may be a deterrent for utilities working within tight capital budgets.

Limited Availability:
Being a specialty product, ester oil may not be as readily available as mineral oil. Its supply chain is also vulnerable to agricultural fluctuations.

Compatibility Concerns:
Not all existing transformer designs are compatible with ester oil. Retrofitting mineral oil transformers for ester oil use may require modifications, adding to project costs.

Cooling Efficiency Issues:
Ester oil has a slightly higher viscosity than mineral oil, which can reduce cooling efficiency in certain transformer designs unless properly accounted for in thermal planning.

Cold Climate Limitations:
In extremely low-temperature environments, ester oil may become too viscous, potentially affecting the transformer's performance if not adequately engineered for cold start conditions

3. CONCLUSIONS

As the global energy sector shifts toward sustainability, the role of eco-friendly materials in critical infrastructure has become increasingly important. This study highlighted the potential of ester oil as a high-performance, environmentally conscious alternative to conventional mineral oil in power transformers. MATLAB-based simulations and performance modeling illustrated that ester oil not only enhances transformer reliability through better thermal stability and aging resistance but also supports environmental goals due to its biodegradability and low fire risk. Despite certain limitations such as higher initial cost and compatibility considerations, the long-term benefits in terms of safety, lifecycle cost, and reduced environmental impact make ester oil a promising solution for modern and future grid systems. The adoption of ester oil thus represents a meaningful step toward building a resilient and greener electrical infrastructure.

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