Faculty of Electrical Engineering

ACCELERATED THERMAL AGEING EFFECT ON INSULATING PAPER IMPREGNATED WITH NATURAL ESTER OIL FOR POWER TRANSFORMER

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A thesis submitted
in fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

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2020

DECLARATION

I declare that this thesis entitled "Accelerated Thermal Ageing Effect on Insulating Paper Impregnated with Natural Ester Oil for Power Transformer" is the result of my own research except as cited in references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Date	:	…………………………………

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature	:	………………………………….
Supervisor Name	:	Ir. Dr. Norazhar bin Abu Bakar
Date	:	………………………………….

DEDICATION

For my beloved parents and family whom without failed to giving their full support till the completion of this research project. Without their love and passion, this project may not be effectively done.

ABSTRACT

Power transformer insulation systems consist of liquid and solid insulation. The liquid insulation is known as transformer oil, while the solid insulation is referred to as paper insulation and pressboard. In principle, materials used as transformer insulation are subjected to ageing process during the operation, which might lead to insulation failure. These ageing processes of transformer insulation are contributed either by temperature, time, moisture and oxygen. Recently, natural ester insulating oil (NEI) was proposed as an alternative to mineral oil (MO) due to the environmental, health and safety concerns from the public. Furthermore, MO filled transformers have a high tendency to cause fire aside from being non-biodegradable. Previous researchers have investigated the NEI properties by comparing with MO under thermal ageing. However, only a few of them conducted the thermal ageing with solid insulation but most of them do not include the effect of metal catalyst which can accelerate the ageing of the transformer. Moreover, most of the researcher compared only one type of NEI with MO in their studies. To overcome these shortcomings, accelerated ageing for two different types of NEI (i.e. palm and rapeseed) was conducted and MO is set as a reference. The first objective was to investigate the properties of oil tested under accelerated thermal ageing. The determination is done by measuring total acid number (TAN), AC breakdown voltage (BDV) and dissolved decay products (DDP). Next, a tensile strength (TS) measurement was conducted in order to identify the condition of kraft paper (KP) immersed in oil tested, and its correlation with oil properties. In order to verify the correlation, a spearman rank correlation was selected to measure the correlation coefficient. On the other hand, the compatibility of NEI with KP was determined by a regression model analysis to distinguish which types of NEI tested had the slowest degradation rate by predicting KP lifespan. The ageing setup was included KP and metal catalyst that was immersed in oils tested. The ageing sample was heated at temperature 130℃ inside the sealed oven for various durations (100, 250, 500, 1000 and 1500 hours). The properties of oils were tested after ageing to determine which oil give the best performance. It was found that the properties of oils tested became worsen as ageing period increased, which also affect the degradation of KP strength. The result shows that the strength of KP immersed in NEI was slowly degraded (palm 67.97%, rapeseed 54.36%) compared to KP immersed in MO (84.04%) at 1500 hours ageing. There was a negative correlation (> -0.8) observed between TS with TAN and TS with DDP for oils tested. While a very strong positive correlation was found between TS and BDV (>0.9) for oils tested. It was also noticed that rapeseed oil was well suited with KP under thermal ageing due to its slow degradation of tensile strength (54.36%). Moreover, the BDV of rapeseed oil maintains high (23 kV) at 1500 hours ageing compare to palm oil (20 kV). Therefore, it can be concluded that rapeseed oil was the most suitable to immersed KP in transformer compare to palm oil.

KESAN PENUAAN HABA DIPERCEPAT TERHADAP KERTAS PENEBAT DIRESAPI DENGAN MINYAK SEMULAJADI UNTUK PENGUBAH KUASA

ABSTRAK

Sistem penebat pengubah kuasa terdiri daripada penebat cecair dan pepejal. Penebat cecair dikenali sebagai minyak pengubah,sementara penebat pepejal disebut sebagai penebat kertas dan papan tekan. Prinsip proses penuaan bahan penebat pengubah semasa beroperasi yang mungkin akan mengagalkan fungsi penebat. Proses penuaan penebat pengubah oleh faktor suhu, masa, kelembapan dan oksigen. Kini, minyak semulajadi (NEI) dicadangkan sebagai alternatif kepada minyak mineral (MO) atas kebimbangan masalah alam sekitar, kesihatan dan keselamatan orang ramai. Tambahan, pengubah yang menggunakan MO mempunyai kecenderungan tinggi untuk menyebabkan kebakaran, tidak biodegradasi. Hanya segelintir penyiasatan menjalankan penuaan haba dengan penebat pepejal dan kebanyakan mereka tidak memasukkan kesan logam pemangkin yang boleh mempercepatkan proses penuaan pengubah. Tambahan, kebanyakan penyelidik membandingkan hanya satu jenis sumber NEI dengan MO dalam kajian. Untuk mengatasi kekurangan ini, proses penuaan haba ke atas dua jenis sumber NEI yang berbeza (iaitu sawit dan "rapeseed") dilaksanakan dan MO sebagai rujukan.Tujuam utama kajian ini adalah untuk mengkaji ciri-ciri minyak yang dikaji selepas eksperimen penuaan haba dijalankan. Ciri-ciri minyak diuji selepas tempoh penuaan bagi menentukan minyak yang manakah memberikan prestasi yang baik. Penentuan dilakukan melalui pengukuran jumlah asid (TAN), kekuatan voltan (BDV) dan produk buangan yang terlarut (DDP) dalam minyak. Kedua, pengukuran kekuatan tegangan (TS) dijalankan bagi melihat keadaan kertas kraft (KP) yang direndam dalam minyak kajian dan terdapat juga hubung kait antara kekuatan KP. Untuk pengesahan, hubung kait jenis Spearman dipilih bagi mengukur pekali hubung kait . Selain itu, kesesuaian NEI dengan KP juga ditentukan melalui analisis model regresi untuk menentukan NEI yang manakah mempunyai kadar kemerosotan paling perlahan dengan meramalkan jangka hayat KP. KP dan logam pemangkin juga direndam dalam minyak yang diuji untuk eksperimen penuaan. Sampel penuaan dipanaskan pada suhu 130 ℃ di dalam ketuhar tertutup untuk pelbagai tempoh (100, 250, 500, 1000 dan 1500 jam). Hasil kajian mendapati bahawa kekuatan KP yang direndam dalam NEI mengalami penuaan yang lambat (sawit 67.97%, "rapeseed" 54.36%) berbanding MO (84.04%) pada 1500 jam penuaan. Berdasarkan hubung kait TS dengan TAN dan TS dengan DDP mempunyai hubung kait negatif yang sangat kuat (>-0.8) pada minyak yang diuji. Selain itu, hubung kait positif yang sangat kuat (>0.9) didapati antara TS dan BDV pada minyak yang diuji. Berdasarkan analisis, minyak berasaskan "rapeseed" sangat sesuai dengan KP di bawah penuaan haba kerana peratusan kemerosotan yang perlahan terhadap kekuatan tegangan (54.36%). Tambahan BDV "rapeseed" kekal tinggi (23kV) pada 1500 jam berbanding dengan sawit (20 kV). Kesimpulannya, minyak "rapeseed" lebih sesuai untuk digunakan bersama KP di pengubah kuasa berbanding minyak sawit.

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LIST OF ABBREVIATIONS

ASTM	-	American standard for testing and material
BS	-	British standard
BDV	-	AC breakdown voltage
CIGRE	-	International council on large electric systems
CTS	-	Coefficient of tensile strength
DDP	-	Dissolved decay products
DP	-	Degree of polymerization
ETS	-	Estimation tensile strength
KP	-	Kraft paper
MO	-	Mineral oil
NEI	-	Natural ester insulating oil
PB	-	Pressboard
PO	-	Palm oil
RO	-	Rapeseed oil
TAN	-	Total acid number
TS	-	Tensile strength

LIST OF PUBLICATIONS

The following publications have been achieved by this research work:

Journal

- Ridzuan, N. L. M., Bakar, N. A., Ghani, S. A., Chairul, I. S. and Aziz, N. H. A., 2019. Comparative study on the accelerated thermal aging behavior between palm and rapeseed natural ester oils. *Bulletin of Electrical Engineering and Informatics,* 8(3), pp. 735 - 743.

- Ridzuan, N. L. M., Bakar, N. A., Ghani, S. A., Chairul, I. S. and Aziz, N. H. A., 2018. Effect of temperature in purification process on the properties of natural ester insulating oils. *ARPN Journal of Engineering and Applied Sciences*, 13(19), pp. 8025 - 8031.

Conference

- Ridzuan, N. L. M. and Bakar, N. A., 2018. Investigation of dissolved decay products in various transformer oil using UV-Vis spectrophotometry. *Symposium on Electrical, Mechatronics and Applied Science 2018*.

- Ridzuan, N. L. M., Bakar, N. A. and Chairul, I. S., 2018. Investigation of moisture progress on insulating oil for power transformer. *MyHVnet Colloquium 2018*

CHAPTER 1

INTRODUCTION

1.1 Power transformer

Power transformers are among the most critical components in electrical distribution systems. It offers an economical way to transfer energy over long distances. The transformer can be considered as the most expensive assets in power transmission and distribution networks. A single power transformer can cost up to five millions of dollars depending on the size and rating (Lai, 2009). Therefore, replacing an old unit with a new transformer for the purpose of increasing the reliability of the power system might not be economically justified. Thus, it is strongly desired to maintain an existing transformer on-service for a lengthier period.

However, aged power transformers are exposed to the faulty and unforeseen failures which will create a major loss of revenue (Lai, 2009). In the meantime, unpredicted fault event can result in a catastrophic loss of power supply to the consumer and potentially affects other power equipment either in substations or industrial buildings (Hoole et al., 2017). Therefore, it is crucial to monitor the health condition of the power transformer in order to prevent any unexpected failure incident to happen. Generally, the overall health condition of the oil-immersed power transformer is determined by the condition of its insulation system. The insulation system of oil-immersed power transformer consists of liquid insulation (oils) and solid insulation (paper and pressboard). The liquid functions as a coolant system, insulator for dielectric breakdown, and minimizing the risk of oxidation (Murugan and Ramasamy, 2019). Whereas the solid insulation (paper) acts as an insulator between windings inside the transformer (Murugan and Ramasamy, 2019). The structure of the transformer is shown in Figure 1.1.

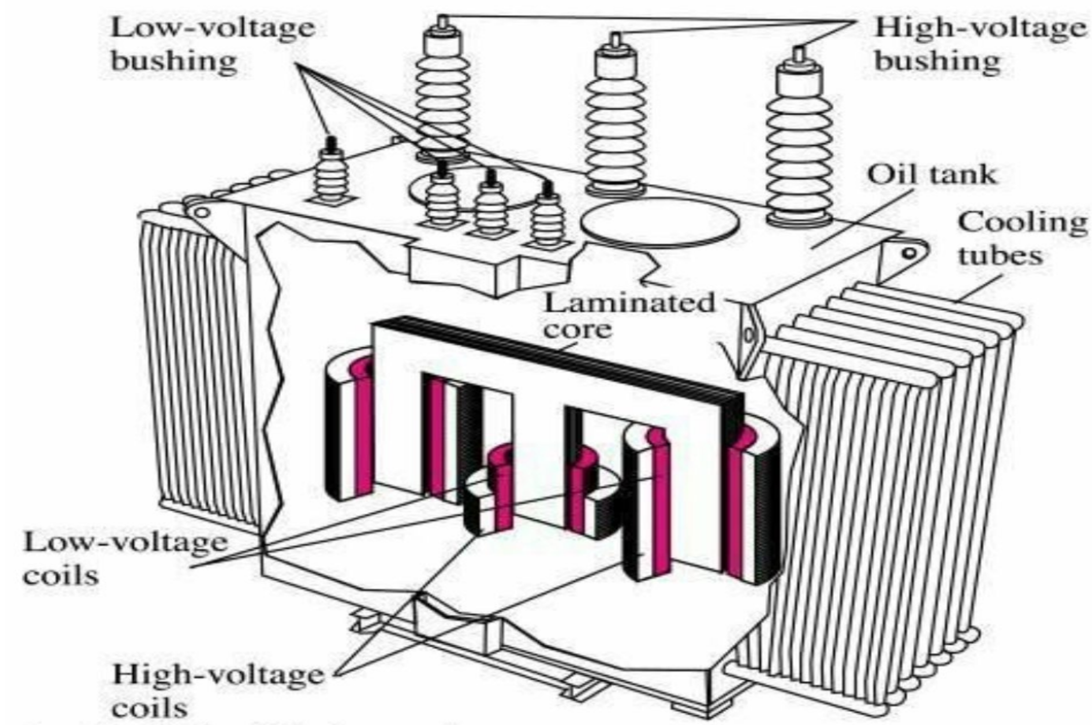

Figure 1.1: Construction of power transformer

According to the report provided by the International Association of Engineering Insurers (IMIA) in 2003, there are 94 cases recorded for the power transformer failures in United State within 1997 to 2001 for the transformer rated at 25 MVA and above (Bartley et al., 2013). Figure 1.2 shows the percentage number of failures and the percentage cost of repair reported by that study. The report has classified the cause of transformer failure into twelve factors which stated in Figure 1.2. Based on the study, it was found that the insulation failures was the highest contributor to the transformer failures and the cost (Bartley et al., 2013).

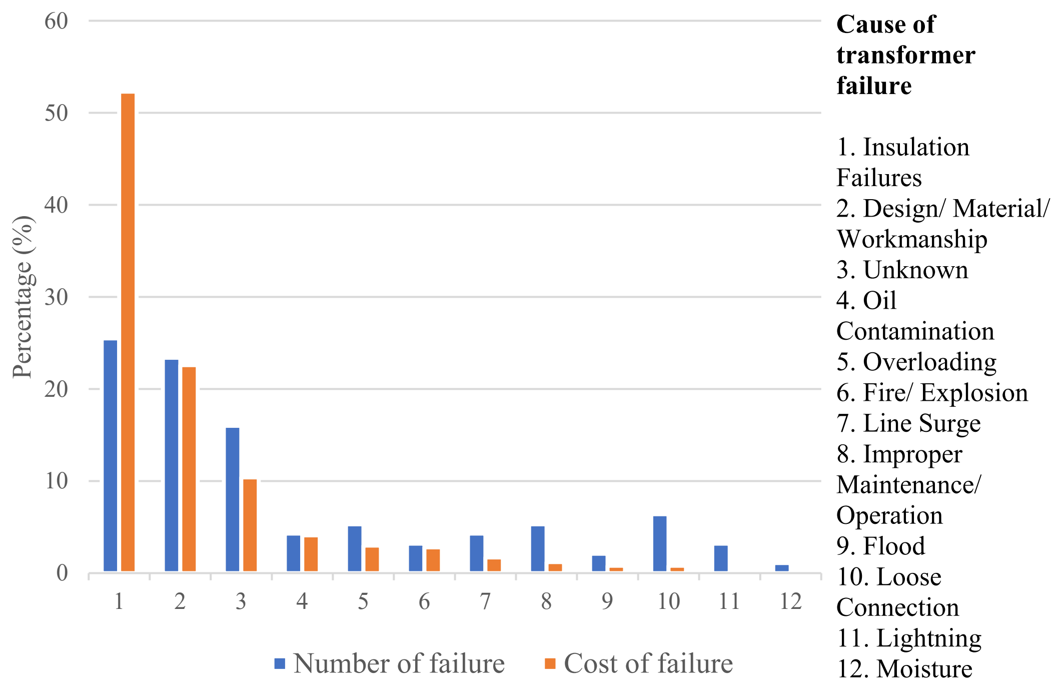

Figure 1.2: Cause of transformer failures (Bartley et al., 2013)

On the other hand, the analysis of transformer failures in India indicates the insulation as the most significant factor for transformer failures. Figure 1.3 shows the distribution of transformer failure component based on Tamil Nadu Electric Utility (TNEU) database between the year 2003 to 2013 (Murugan and Ramasamy, 2019). The generation, transmission, and distribution of electric power across 32 districts in the state of Tamil Nadu were under TNEU responsibility. About 842 substations were operating at various voltage levels and 343 power transformer failures were recorded within the year 2003 to 2013. The power rating of the transformers was within the range between 10 to 315 MVA, and the voltage was varied between 33 kV to 400 kV. The component failures were classified into five primary failure modes which are electrical, thermal, mechanical, insulations degradation (oil and paper) and others as listed in Table 1.1. Based on tabulated data presented in Figure 1.3, it was found that insulation was the most significant cause of failure (36.74% of failures) followed by winding (21.30%), bushings (15.70%), on-load tap changer (12%) and core (3.5%) of failures (Murugan and Ramasamy, 2019).

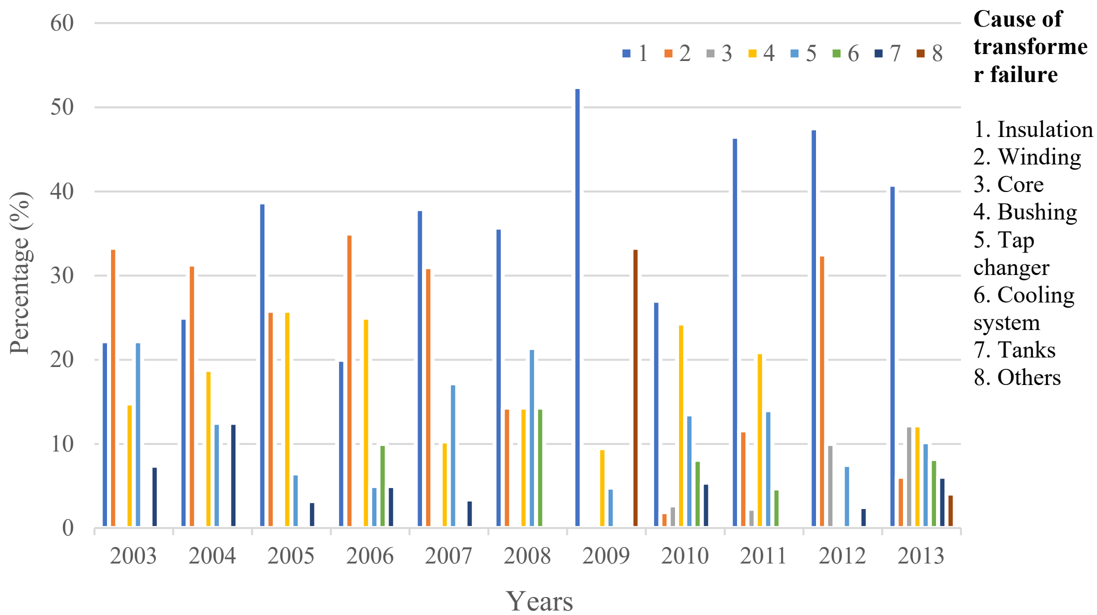

Figure 1.3: Power transformer component failures over the period 2003 to 2013 (Murugan and Ramasamy, 2019)

Table 1.1: Power transformer component primary and sub failure modes (Murugan and Ramasamy, 2019)

Components	Primary failure modes	Sub failure modes
1. Oil - paper insulation	Degradation (chemical)	Water in oil. Water in paper. High temperature of oil and paper. Ageing of oil and paper due to thermal decomposition of oil and paper insulation and contamination from moistures.
2. Winding	Electrical	Short-circuit between turns. Short-circuit between strands. Short-circuit to ground.
	Thermal	Overloading of the transformer. Cooling system failure. Arcing. Low-energy sparking. Partial discharge. Local over heating of the winding insulating material, and hot spots

	Mechanical	Conductor tilting. Conductor bending. Bulk movement of winding. Axial instability. Loose clamping structure. Winding buckling (hoop/compression types). Winding internal lead deformation.
3. Core	Electrical	Short-circuited core laminations. Multiple core grounding. Ungrounded core.
	Mechanical	Core deformation.
4. Bushing	Electrical	Short-circuit between layers.
	Thermal	Network overloading. Low-energy sparking. Partial discharge. Local over heating of the bushing insulating material, and hot spots.
	Mechanical	Porcelain damage due to electrical flashover, lightning, external short circuit force, and cracks in outer coatings.
5. Tap changer	Electrical	Open circuit contacts.
	Thermal	Coking of contacts.
	Mechanical	Drive mechanism fault.
6. Cooling system	Electrical/ Mechanical	Pump. Fan. Radiator.
7. Tanks	Mechanical/ Thermal	Leakage. Rupture.
8. Others	Unknown causes	Operational errors. Lack of maintenance. Protection system failure