EMPLOYMENT OF PROBABILITY-BASED MULTI-RESPONSE OPTIMIZATION IN HIGH VOLTAGE THERMOFLUIDS

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Abstract:

Introduction/purpose: Researchers of fluids for high voltage engineering application always experience problems when selecting and recommending specific fluids suitable for high voltage application. This is due to the dual functionality of fluids required for high voltage equipment.

Methods: This study introduced and employed a probability-based multi-objective optimization technique in the selection of high voltage thermofluids. Beneficial and unbeneficial preferable probability utility indexes were employed based on the desired properties of oils.

Results: It was shown that the nanofluid with 0.6 wt% Al_2O_3 is the most promising candidate for high voltage equipment compared to other produced fluids considered. It is also noteworthy to state that coconut oil exhibited better performance efficiency compared to standard oil. This study also identifies that the produced Jatropha oil was inadequate for high voltage equipment.

Conclusion: In conclusion, a preliminary study essential for final usage of 0.6 wt% Al_2O_3 nanofluids and coconut oil for high voltage equipment is recommended as well as the improvement of the performance characteristics of Jatropha oil for usage in high voltage equipment.

Keywords: preferable probability optimization, high voltage equipment, thermofluids, physicochemical properties, dielectric strength.

Introduction

High voltage engineering is an integral area of electrical and mechanical engineering. A lot of devices have been made for high voltage application - power transformers, switchgears, control equipment, communicating devices, and insulators, to mention but a few. The quality of insulating fluids used in such equipment is essential for its wellbeing and efficiency (Oparanti et al, 2020; Oparanti et al, 2022). This study comes with the motivation to apply a novel multi-objective approach in the selection of optimal processing conditions or better performance fluids for high voltage equipment.

Conventional mineral oil has been used in high voltage equipment due to its unique and multifunctional characteristics, which are efficient cooling and dielectric capacity. However, due to mineral oil non-biodegradability and other intricate production tendencies, researchers have worked on the production of alternative fluids for high voltage engineering. Abeysundara et al (2001) produced and examined the properties of coconut oil as an alternative for transformer mineral oil. Sitinjak et al (2003) examined the characteristics of palm oil and its derivative for high voltage equipment. Hosier et al (2009) studied the selection of a suitable vegetable oil for high voltage engineering. Garba et al (2013) produced and characterized Jatropha oil for transformer application. Peppas et al (2016a, 2016b) produced ultrastable natural ester-based nanofluids for high voltage engineering. Oparanti et al (2021a) developed a nanofluid from palm kernel oil for high voltage engineering. Oparanti et al (2021b), in addition to their previous work, analyzed AC breakdown of their synthesized nanofluids from palm kernel oil. In all of these studies, with the ones not mentioned, there has been a challenge in selecting a specific oil sample suitable for high voltage application, considering the dual functionality of a typical high voltage equipment oil. Hence, this study has addressed this challenge by introducing and employing a probability-based optimization technique for multiple performance characteristics of high voltage engineering oil.

Consequently, several techniques such as Ashby’s method (Ashby, 2000; Ashby et al, 2004), the TOPSIS method (Deshmukh & Angira, 2019), the grey relational analysis method (Abifarin, 2021; Abifarin et al, 2021a, 2021b, 2021c; Awodi et al, 2021; Abifarin et al, 2022; Abifarin & Ofodu, 2022), and the intersection multi-objective probability method (Wang & Teng, 2021; Zheng, 2022) have been used for multiple objective optimization in several applications; probability-based multi-objective optimization has proven to be simple and more efficient (Zheng, 2022).

Hence, this study selected some data (Abeysundara et al, 2001; Garba et al, 2013; Oparanti et al, 2021a) in high voltage engineering oil development and then the new multi-objective probability optimization technique was employed for the first time to determine the most efficient oil sample among other samples in the study.

Research method

The beneficial utility index method is applied to a desired characteristic which should be as high as possible. The index characteristic indicator contributes positively to a partial preferable probability. Equation 1 is used to compute the partial positive probability index (Pij), while equation 2 is used to compute the normalized factor (α_j) of the jth utility index of the performance characteristic indicator.

$$Pij = \alpha_{ij} X_{ij},\ i = 1, 2,...,n;\ j = 1, 2,..m \quad (1)$$

$$\alpha_j = 1/(\mathrm{n}\overline{X}_j) \quad (2)$$

where X_{ij} is the jth beneficial utility index of the characteristic performance indicator of the ith number of sample, n is the total number of samples considered in the study, m is the total number of utility indices of each sample involved, and X_j is the value of the arithmetic mean of the utility index of the sample characteristic performance indicator. The performance characteristics considered for the beneficial utility index are shown in Table 1:

Table 1 – Beneficial utility high voltage characteristics
Таблица 1 – «Чем больше, тем лучше» характеристики изоляционного масла
Табела 1– Карактеристике изолационог уља типа „што више – то боље”

Performance characteristics	Beneficial utility discussion	Reference
Activation energy (eV/mol)	The higher the activation energy, the harder it becomes to reduce the viscosity of the liquid at elevated temperature. In other words, a higher activation energy of a fluid leads to a good cooling integrity of the fluid.	(Badicu et al, 2011; Liu et al, 2019; Liu et al, 2020; Oparanti et al 2021a)

Performance characteristics	Beneficial utility discussion	Reference
Breakdown voltage/Dielectric strength (kV)	Breakdown voltage or dielectric strength of an insulator is the minimum voltage that makes the portion of an insulator to experience electrical breakdown and become electrically conductive. Also the higher the breakdown voltage of a fluid, the less contaminant the oil. In other words, as high as possible breakdown voltage is required for high voltage equipment.	(Lee et al, 2012; Peppas et al, 2016a, 2016b; Abd-Elhady et al, 2018; Ghoneim et al, 2021; Oparanti et al, 2021a; Asse et al, 2022)
Flash point (ºC)	Insulating fluids for high voltage equipment should exhibit a high flash point. This prevents fire outbreak, interrupted power supply and economic loss.	(Kumar et al, 2014; Oparanti et al, 2021a; Oparanti et al, 2022; Minkner & Schmid, 2022)

The unbeneficial utility index method is applied to a desired characteristic which should be as low as possible, i.e. minimization type of optimization is desired. The index characteristic indicator contributes negatively to a partial preferable probability.

Equation 3 is used to compute the partial negative probability index (Pij), while equation 4 is used to compute its normalized factor (β_j) of the jth utility index of the performance characteristic indicator.

$$Pij = \beta_{ij}(X_{jmax} + X_{jmin} - X_i),\ i = 1, 2,...,n;\ j = 1, 2,..m \qquad (3)$$

$$\beta ij = 1/[n(X_{j\min} + X_{j\max}) - nX_j] \qquad (4)$$

Table 2 – Unbeneficial utility high voltage oil characteristics
Таблица 2 – «Чем меньше, тем лучше» характеристики изоляционного масла
Табела 2 –Карактеристике изолационог уља типа „што мање – то боље"

Performance characteristics	Unbeneficial utility discussion	Reference
Cloud point	The cloud point of an insulating fluid is the temperature at which the fluid begins to condense, i.e. the smaller the cloud point of an insulating fluid, the better it is for high voltage equipment	(Garba et al, 2013; Du et al, 2013; Oyelaran et al, 2020)
Viscosity	High viscosity of a fluid usually causes poor atomization of the fluid, meaning minimization is required for high voltage equipment	(Hosier et al, 2006; Garba et al, 2013; Srinivasa & Surendra, 2019)
Specific gravity	Specific gravity is used to examine whether an object will float or sink in water. In other words, if the specific gravity of a fluid is less than one, it means that the fluid will float in water. Lower specific gravity is required to enable the dewatering of the fluid during transformer maintenance.	(Gong et al, 2018; Lin et al, 2021)
Density	Lower density of a fluid for high voltage equipment is required because it enhances mobility of the fluid. Mobility of the fluid is required for efficient equipment cooling.	(Yaacob & Alsaedi, 2015)
Moisture content	Moisture content has a negative effect on the insulating and dielectric properties of a transformer oil. No water content or as small as possible water content is desired for high voltage equipment	(Ofodu & Abifarin, 2021; Zhang et al, 2021)

Furthermore, the conclusive preferable probability of the analysis is the product of the individual partial preferable probability of a corresponding candidate sample. Afterwards, the ranking is done to show the candidate sample with the best performance characteristics.

Analysis and discussion of the results

Activation energy and breakdown voltage

Oparanti et al (2021a) developed nanofluids and examined their activation energy and breakdown voltage. However, the analysis did not reflect conclusively which oil sample is the best candidate for high voltage equipment. Table 3 shows the oil samples and their corresponding activation energies and breakdown voltages.

Table 3 – Activation energy and breakdown voltage of high voltage fluids
Таблица 3 – Энергия активации и напряжение высоковольтного пробоя жидкостей
Табела 3 – Активациона енергија и напон пуцања флуида за високонапонску опрему

Samples	Activation energy (eV/mol)	Breakdown voltage (kV)
Ester oil	0.04	21
Ester + 0.2 wt% Al_2O_3	0.09	23
Ester + 0.4 wt% Al_2O_3	0.09	27
Ester + 0.6 wt% Al_2O_3	0.09	29
Ester + 0.8 wt% Al_2O_3	0.09	29
Ester + 1 wt% Al_2O_3	0.09	27
Ester + 0.2 wt% TiO_2	0.047	26
Ester + 0.4wt% TiO_2	0.047	27
Ester + 0.6 wt% TiO_2	0.05	28
Ester + 0.8 wt% TiO_2	0.06	28
Ester + 1 wt% TiO_2	0.08	28

The data presented in Table 3 was analyzed using the beneficial utility index as the higher-the-better characteristics desired for high voltage equipment. The resulting analysis is displayed in Table 4. The multi-objective optimization shows that two oil samples exhibited the best performance - the nanofluids with 0.6 and 0.8 wt% Al_2O_3 nanoparticles. However, to save costs and to reduce agglomeration of nanoparticles in the fluid, the nanofluid with 0.6 wt% Al_2O_3 is the most promising candidate for high voltage equipment. In addition, it is recommended to study the effect of Al_2O_3 nanoparticles using the 1wt% stepwise increase instead of the used 2wt% stepwise increase of activation energy and breakdown voltage of ester oil. This will show that perhaps 0.7 wt% has better activation energy and breakdown voltage.

Table 4 – Partial (Pij) and total preferable (Pt) probabilities of activation energy and breakdown voltage of various fluids

Таблица 4 – Частичная (Pij) и полная (Pt) предпочтительные вероятности энергии активации и напряжения пробоя различных жидкостей

Табела 4 – Делимичне (Pij) и укупне (Pt) пожељне вероватноће активационе енергије и напона пуцања разних флуида

Samples	Pij of activation energy	Pij of breakdown voltage (kV)	Pt*100	Rank
Ester oil	0.052	0.072	0.372	9
Ester + 0.2 wt% Al_2O_3	0.117	0.079	0.917	4
Ester + 0.4 wt% Al_2O_3	0.117	0.092	1.077	2
Ester + 0.6 wt% Al_2O_3	0.117	0.099	1.157	1
Ester + 0.8 wt% Al_2O_3	0.117	0.099	1.157	1
Ester + 1 wt% Al_2O_3	0.117	0.092	1.077	2
Ester + 0.2 wt% TiO_2	0.061	0.089	0.542	8
Ester + 0.4wt% TiO_2	0.061	0.092	0.562	7
Ester + 0.6 wt% TiO_2	0.065	0.096	0.621	6
Ester + 0.8 wt% TiO_2	0.078	0.096	0.745	5
Ester + 1 wt% TiO_2	0.104	0.096	0.993	3

Physicochemical characteristics and dielectric strength

Garba et al (2013) produced Jatropha oil, examined its properties, and compared it with diesel oil and transformer oil to see which one would perform better for transformer application. The performance characteristics of various oils are displayed in Table 5.

The flash point and dielectric strength were analyzed using the beneficial utility index (see Table 1) while the rest of the characteristics in Table 5 were analyzed using the unbeneficial utility index (see Table 2). The result showed that the developed Jatropha oil exhibited lesser performance for high voltage equipment compared to the other two standard oils. This means that further study is essential to improve the performance characteristics of Jatropha oil for high voltage equipment. Many reports have shown that the addition of nanoparticles and the improvement of oil production can improve the performance efficiency of the oil for high voltage equipment (Jin et al, 2014; Peppas et al, 2016a, 2016b; Rafiq et al, 2016; Muangpratoom & Pattanadech, 2018; Oparanti et al, 2022).

Table 5 – Physicochemical characteristics and dielectric strength for high voltage engineering
Таблица 5 – Физико-химические характеристики и диэлектрическая прочность в области техники высоких напряжений
Табела 5 –Физичко-хемијске карактеристике и диелектрична снага у области енергетике високог напона

Oil samples	Flash point (ºC)	Cloud point (ºC)	Viscosity (cst)	Specific gravity	Density (g/cm^3)	Dielectric strength (kV)
Diesel	65	5	2.86	0.792	0.8162	20
Jatropha oil	150	14	8.2	0.848	0.725	22
Transformer oil	140	7	9.3	0.89	0.89	24

Table 6 – Partial (Pij) and total preferable (Pt) probabilities of the physicochemical properties and dielectric strength of fluids
Таблица 6 – Частичная (Pij) и полная (Pt) предпочтительные вероятности физико-химических характеристик и диалектрической прочности жидкостей
Табела 6 – Делимичне (Pij) и укупне (Pt) пожељне вероватноће физичко-хемијских карактеристика и диелектричне снаге флуида

Oil samples	(Pij) of flash point	(Pij) of cloud point	(Pij) of viscosity	(Pij) of specific gravity	(Pij) of density	(Pij) of dielectric strength	Pt*1000	Rank
Diesel	0.183	0.448	0.577	0.356	0.647	0.303	3.302	1
Jatropha oil	0.423	0.16	0.246	0.334	0.721	0.333	1.331	3
Transformer oil	0.395	0.384	0.177	0.317	0.587	0.364	1.817	2

Abeysundara et al (2001) produced a coconut oil, evaluated its performance characteristics and compared it with a standard oil for high voltage equipment. The properties of the two different oil types are presented in Table 7.

Table 7 – Properties of coconut oil and standard oil
Таблица 7 – Свойства кокосового масла и стандартного масел
Табела 7 – Својства кокосовог уља и стандардног уља

Oil type	Dielectric strength (kV)	Flash point (ºC)	Moisture content (mg/Kg)	Viscosity (cst)	Density (Kg/dm^3)
Coconut oil	60	225	1	29	0.917
Standard oil	50	154	1.5	13	0.895

The multi-objective optimization analysis was done and presented in Table 8 based on the conditions in Table 1 and 2. It is interesting to note that the produced coconut oil exhibited a higher performance tendency for high voltage equipment compared to standard oil. This shows that it is a good candidate for high voltage engineering. Therefore, further study such as ageing, direct application of the oil in a typical high voltage equipment is recommended.

Table 8 – Partial (P_{ij}) and total preferable (P_t) probabilities of the oil properties
Таблица 8 – Частичные (Pij) и полные (Pt) предпочтительные вероятности свойств масла
Табела 8 – Делимичне (P_{ij}) и укупне (P_t) пожељне вероватноће својстава уља

Oil type	(P_{ij}) of dielectric strength	(P_{ij}) of flash point	(P_{ij}) of moisture content	(P_{ij}) of viscosity	(P_{ij}) of density	P_t	Rank
Coconut oil	0.546	0.594	0.6	0.312	0.492	2.984	1
Standard oil	0.455	0.406	0.4	0.696	0.504	2.593	2

Conclusion

This study successfully introduced and employed a probability-based multi-response optimization technique in the selection of high voltage thermofluids. The results showed the possibility of the employment of the probability-based multi-objective optimization technique in the production and selection of high voltage equipment oil. It was found out that the nanofluid with 0.6 wt% Al_2O_3 is the most promising candidate for high voltage equipment compared to other produced fluids in the study of Oparanti et al (2021a). It is also noteworthy to state that coconut oil exhibited better performance efficiency compared to standard oil in the study of Abeysundara et al (2001). However, this study identifies that Jatropha oil produced by Garba et al (2013) was inadequate for high voltage equipment. Hence, preliminary study essential for the final usage of 0.6 wt% Al_2O_3 nanofluids and coconut oil for high voltage equipment should be done while the performance characteristics of Jatropha oil for high voltage equipment should be improved. In conclusion, the multi-objective optimization technique has been successfully employed in the selection of fluids for high voltage equipment. It is clear from the study that the analysis is simple to apply. Hence, it is recommended that the probability multi-objective optimization technique be subsequently employed when selecting the most efficient fluid for high voltage equipment.

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ПРИМЕНЕНИЕ ОПТИМИЗАЦИИ С НЕСКОЛЬКИМИ ВЫХОДАМИ, ОСНОВАННОЙ НА ВЕРОЯТНОСТИ, ДЛЯ ЖИДКИХ ТЕПЛОНОСИТЕЛЕЙ ВЫСОКОВОЛЬТНОГО ОБОРУДОВАНИЯ

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РУБРИКА ГРНТИ: 30.17.00 Механика жидкости и газа,
47.09.00 Материалы для электроники и радиотехники
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Исследователи, занимающиеся жидкостями, предназначенными для использования в технике высоких напряжений, зачастую сталкиваются с проблемами при выборе или при рекомендации соответствующей жидкости, подходящей для использования в технике высоких напряжений. Это связано с двойной функциональностью жидкостей, необходимых для высоковольтного оборудования.

Методы: В данной статье представлен и применен метод многоцелевой оптимизации, основанный на вероятности, при выборе теплоносителя для высоковольтного оборудования. В *зависимости от ожидаемых характеристик масла применялись индексы предпочтительной вероятности полезности, типа «чем больше, тем лучше» и «чем меньше, тем лучше».*

Результаты: Результаты исследования показали, что наножидкость с содержанием 0.6 wt% Al_2O_3 является наиболее перспективным кандидатом для высоковольтного оборудования по сравнению с другими испытанными жидкостями. Также важно отметить, что кокосовое масло показало лучшие результаты по сравнению со стандартным маслом. В ходе исследования также выявлено, что выработанное масло ятрофы непригодно для высоковольтного оборудования.

Выводы: Рекомендуется провести предварительное исследование, необходимое для конечного использования наножидкостей с содержанием 0.6 wt% Al_2O_3, а также кокосового масла в технике высокого напряжения. Также рекомендуется улучшить характеристики масла, выработанного из растения ятрофа для использования в технике высокого напряжения.

Ключевые слова: оптимизация предпочтительной вероятности, высоковольтное оборудование, теплоносители, физико-химические свойства, диэлектрическая прочность.

ПРИМЕНА ОПТИМИЗАЦИЈЕ СА ВИШЕ ИЗЛАЗА ЗАСНОВАНЕ НА ВЕРОВАТНОЋИ ФЛУИДА ДА ПРЕНОСЕ ТОПЛОТУ У ВИСОКОНАПОНСКОЈ ОПРЕМИ

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ОБЛАСТ: машинство, материјали
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: При избору одговарајућег флуида погодог за примену у високонапонској опреми наилази се на проблеме. Узрок томе је двострука функционалност флуида која се захтева за високонапонску опрему.

Методе: Овај рад уводи и примењује технику вишециљне оптимизације засноване на вероватноћи приликом селекције флуида за пренос топлоте у високонапонској опреми. Индекси корисности пожељне вероватноће типа „што више – то боље” и *типа „што мање – то боље” примењени су зависно од жељених карактеристика уља.*

Резултати: Показано је да је нанофлуид са 0,6 wt% Al_2O_3 најпогоднији за високонапонску опрему у односу на остале разматране произведене флуиде. Важно је поменути да је кокосово уље показало боље перформансе у поређењу са стандардним уљем. Указано је, такође, и да произведено уље биљке Jatropha није погодно за високонапонску опрему.

Закључак: Препоручује се прелиминарна студија, неопходна за крајње коришћење нанофлуида са 0,6 wt% Al_2O_3,као и кокосовог уља за високонапонску опрему. Такође, препорука је да се побољшајукарактеристике уља биљке Jatropha ради коришћења у високонапонској опреми.

Кључне речи: оптимизација пожељне вероватноће, високонапонска опрема, флуиди за пренос топлоте, физичко-хемијска својства, диелектрична снага.

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