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Comparative Study on the AC Breakdown Voltage of Palm Fatty Acid Ester Insulation Oils Mixed With Iron Oxide Nanoparticles

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ABSTRACT

Nowadays, nanotechnology has become one of the most important research fields in both the academia and industry and it has been shown in previous studies that nanoscale materials are beneficial for transformers. In this regard, the objective of this study is to compare the AC breakdown voltage of palm fatty acid ester (PFAE) oils mixed with iron oxide (Fe_3O_4) nanoparticles. The PFAE-based nanofluids are prepared based on two methods suggested in literature. Method I: the concentration of Fe_3O_4 nanoparticles is weight-based (g/l), i.e. gram for each litre of PFAE oil. Method II: the concentration of Fe_3O_4 nanoparticles is based on volume-fraction (%). The AC breakdown voltage test is conducted on the PFAE-based nanofluids in accordance with the ASTM D1816 standard test method. Weibull statistical analysis is carried out to analyse the AC breakdown voltage of fresh PFAE oil and PFAE-based nanofluids. It is found that there is enhancement of the AC breakdown voltage for all PFAE-based nanofluids with the exception of one sample prepared using Method II (0.01% Fe_3O_4 nanoparticles).

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1. INTRODUCTION

High Voltage engineering is widely used in power systems, especially for power generation, transmission and distribution. Insulation plays a prominent role in high voltage systems such as rotating machines, power capacitors, power transformers, switchgears, circuit breakers and power cables to ensure that the systems are in best performance. The lifespan of high voltage systems is heavily dependent on the reliability of the insulation of the systems and this includes the insulation materials [1]-[3]. The insulation media used in high voltage systems can be generally classified as solids, liquids and gases. In general, solid and liquid insulating media are commonly used for transformers. Solid insulating media include barriers, blocks and spacers made of cellulose pressboard or wood whereas liquid insulating media include petroleum-derived mineral oils, synthetic liquids as well as vegetable-based oils [4]. Mineral oils are typically used as insulation liquids for transformers due to their excellent dielectric and cooling properties, as well as low cost. Moreover, mineral oils are commercially available in the market. However, despite the benefits of mineral oils, these oils are derived from petroleum, which is a non-renewable and non-sustainable source, and therefore, these oils are not a long term option for insulating transformers [5]–[7]. For this reason, there is a critical need to develop alternative insulating media in replacement of conventional mineral oils. Palm oil is derived from oil palm fruits and it has great potential for use as an insulating medium for transformers. This oil offers a number of benefits since it is biodegradable and it has high cooling stability and good oxidation stability [8],[9]. More importantly, it is potential substitute of mineral oils because of its excellent dielectric properties. Palm fatty acids ester (PFAE) was developed in 2006 by Lion Corporation as insulation oil for transformer [10]. PFAE is not only environmentally friendly but it also has superior insulation performance.

Much effort has been made to improve the dielectric performance of insulation oils and one of these involves blending the insulation oils with nanoparticles. Such mixtures are known as nanofluids [11]–[16]. Even though the concept of nanofluids was initiated by Choi in 1993 for thermal conductivity enhancement, studies on the dielectric properties of nanofluids as insulating media had only begun in 1998 by Segal et al. [17]. According to Lv et al. [13], the nanoparticles is divided into three groups i.e conductive nanoparticles, semi-conductive nanoparticles and insulating nanoparticles. There is a lack of interest in conductive nanoparticles among researchers because of their high tendency to agglomerate. Statistical techniques can be used to determine the performance of sample by using AC breakdown voltage test. In this regard, the main purpose of statistical techniques is to estimate the AC breakdown voltage (also known as the withstand voltage) based on the probability of distribution data [18]. The objective of this study is to compare the AC breakdown voltage of PFAE-based nanofluids prepared using two different methods that will be discussed in the following section. The PFAE-based nanofluids are prepared by dispersing iron oxide nanoparticles (Fe_3O_4), a type of conductive nanoparticles in PFAE oils. Weibull statistical analysis is then carried out to analyse and interpret the data.

2. EXPERIMENT PREPARATION

2.1. Sample Preparation

The natural ester used for this study was palm fatty acid ester (PFAE), which is a product derived from palm oil, supplied by Lion Company Sdn. Bhd. A conductive nanoparticle was used to prepare the PFAE-based nanofluids. The nanoparticle was Iron Oxide (Fe_3O_4) with size range of 15–20 nm. Oleic acid was used as the surfactant, whereby 0.5 ml of oleic acid was mixed with the PFAE oil samples before the addition of the Fe_3O_4 nanoparticles in order to modify the stability of the mixtures [17]. The PFAE-based nanofluids were prepared using two methods i.e. Method I: weight-based method [19] and Method II: volume-fraction method [20].

In general, for each method, there are three steps involved in the preparation of nanofluids, i.e. (1) sample weighing, (2) homogenizer treatment and (3) vacuum process. In the first step, the nanoparticle powders were weighed using an analytical balance. For Method I, the amount of Fe_3O_4 nanoparticles was directly measured using the analytical balance [19], whereby the concentration of the Fe_3O_4 nanoparticles was kept fixed at 0.01 g/l. On the other hand, for Method II, the weight of Fe_3O_4 nanoparticles to be used was determined on the basis of volume fraction. The weight of the Fe_3O_4 nanoparticles is given by the following formula [20],[21]:

$$W_{nm} = \frac{\rho_{nm} \times V_{oil} \times PVF_{nm}}{100} \tag{1}$$

Where W_{nm} is the weight of the Fe_3O_4 nanoparticles (g), ρ_{nm} is the density of Fe_3O_4 nanoparticles (g/cm3), V_{oil} is the volume of the PFAE oil sample (ml) and PVF_{nm} is the volume fraction of the Fe_3O_4 nanoparticles (%). For example, the weight of the Fe_3O_4 nanoparticles required for 500 ml of insulation oil is 0.2475 g if the density and volume fraction of the nanoparticles is 4.95 g/cm3 and 0.01%, respectively. Table 1 shows the concentration of the Fe_3O_4 nanoparticles and its corresponding weight for each 500 ml PFAE-based nanofluids from Method I and Method II. The volume of the surfactant is also shown in Table 1.

The second step involves homogenizer treatment. In this step, the samples were homogenized in order to disperse the Fe_3O_4 nanoparticles. It is worth noting here that this treatment is able to break up nanoparticle aggregates and achieve well-dispersed nanoparticles [19],[22],[23]. The homogenizer was set at 50% for pulse-mode operation (cycle) and 50% for homogenizer power (amplitude). A probe with a diameter of 40 mm and length of 100 mm was used to disperse the Fe_3O_4 nanoparticles. The third step is the vacuum process, whereby the samples were placed in a vacuum oven to remove bubbles, moisture and gases that may have appeared during the homogenizer treatment. The samples were left in the vacuum oven for at least 72 hours at 70°C, according to the procedure given in [19]. The samples were then stored in sealed beakers until further analysis.

2.2. AC Breakdown Voltage Test

It is known that all electrical systems require testing to ensure that they will be in best performance condition during operation. In this case, it is important to ensure that insulation oil is in good condition during typical operating conditions of the transformer. The insulation oil plays a vital role to insulate the components in the transformer and it must be able to withstand thermal and electrical stresses. The quality of the insulation oil is assessed by its resistivity, permittivity and AC breakdown voltage. The AC breakdown voltage test is one of the common test procedures used to evaluate the quality of the insulation oil and therefore, the AC breakdown voltage was chosen as the measure of the quality of the PFAE-based nanofluids in this study.

The AC breakdown voltage of the PFAE-based nanofluids was measured using Megger OTS60PB portable oil test set which complies with the ASTM D1816 standard test method. Spherical electrodes with diameter of 36 mm were used in this study and the gap distance between the electrodes was 1.0 mm. The volume of each PFAE oil sample was kept fixed at 500 ml. The AC breakdown voltage test was conducted by increasing the voltage supply gradually at a rate of 0.5 kV/s until breakdown occurs. A total of 40 breakdown voltages were recorded for each PFAE oil sample and the data were analysed using statistical analysis.

Table 1. Preparation of PFAE-based nanofluids using method I and method II

Method	Fe_3O_4 nanoparticle concentration	Weight of Fe_3O_4 nanoparticles per 500 ml PFAE oil (g)	Volume of surfactant Per 500 ml PFAE oil (ml)
Method I	0.01 g/l	0.0050	0.25
Method II	0.01%	0.2457	0.25
Method II	0.02%	0.4950	0.25
Method II	0.03%	0.7425	0.25

2.3. Weibull Statistical Analysis

Weibull statistical analysis was used to analyse the AC breakdown voltage data for all samples. The two-parameter Weibull plot was used for this analysis. The breakdown probabilities were determined using the following formula [24]:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \tag{2}$$

where *F(x)* is the probability of the AC breakdown voltage, x is the AC breakdown voltage, β is the shape parameter and η is the scale parameter. The Weibull plot was plotted based on the estimation of the shape parameter, scale parameter and correlation coefficient. The correlation coefficient, ρ is a measure of how well the linear model fits the data between the median ranks. The correlation coefficient has a value between –1 to +1. In general, a correlation coefficient close to +1 indicates that there is a strong positive correlation between two variables, which is evident from the upward trend in the graph. On the other hand, a correlation coefficient close to –1 indicates that there is a strong negative correlation between two variables, which is also evident from the downward trend in the graph.

Plotting the Weibull probability plot is easy for those who are familiar with linear plots and basic algebra. The equation used to produce a linear plot is given by Equation (3), where y is the dependent variable, x is the independent variable, m is the slope and b is the intercept.

$$y = mx + b \tag{3}$$

Equation (2) was manipulated in order to give the following equation:

$$y = \beta x - \beta \ln(\eta) \tag{4}$$

equation (4) is a linear equation, whereby β is the slope and $\beta ln(\eta)$ is the intercept. The slope can be determined from the linear plot, which in turn, gives the value of the shape parameter, β. It shall be noted that the x-axis represents the AC breakdown voltage, which is arranged from the lowest to the highest value. The y-axis represents the median rank. The median rank is determined for each AC breakdown voltage value and is given by the following equation [24]:

$$MR = \frac{j - 0.3}{N + 0.4} \tag{5}$$

where j is the sequence of data from 1 to N and N is the number of data. For example, if the number of AC breakdown voltages recorded per experiment is 40 (which is the case in this study), then $N = 40$. Thus, the median rank needs to be determined 40 times, i.e. one median rank for each AC breakdown voltage where $j = 1,\ldots,40$. The median rank is in the form of a ratio, with a value greater than 0 and less than 1. The scale parameter, η, indicates the spread of the distribution and it can be used to stretch or squeeze the graph [24]. In this case, the probability of the AC breakdown voltage when $x=\eta=\beta$ is shown in Equation (6).

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] = 1 - \exp(-1) = 0.632 = 63.2\% \tag{6}$$

In general, the shape parameter can be determined once the correlation coefficient and median rank are known. The scale parameter can be best estimated after plotting the graph.

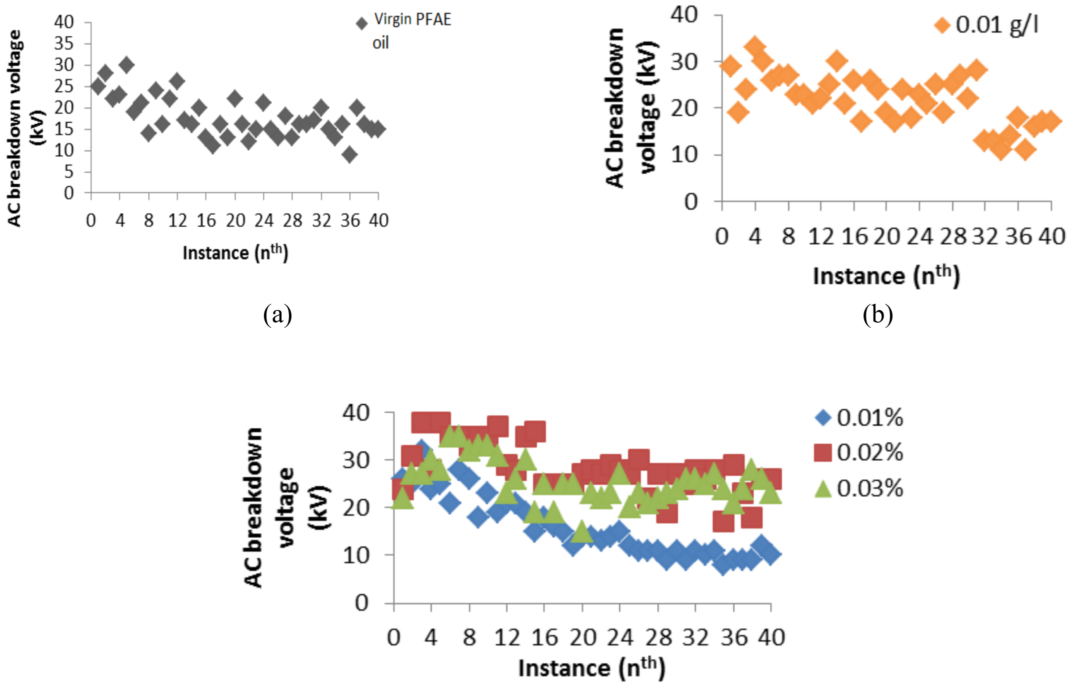
3. RESULTS AND ANALYSIS

3.1. AC Breakdown Voltage

The distribution of the AC breakdown voltage for the virgin PFAE oil, PFAE-based nanofluid prepared using Method I and PFAE-based nanofluid prepared using Method II are shown in Figures 1 (a), (b) and (c), respectively. It can be seen from Figure 1 (a) that the lowest AC breakdown voltage for the virgin PFAE oil is 9 kV at instance 36 whereas the highest AC breakdown voltage is 30 kV at instance 5. Similarly, it can be seen from Figure 1 (b) that the lowest AC breakdown voltage for the PFAE-based nanofluid prepared using Method I is 11 kV at instance 34 and 37, while the highest AC breakdown voltage is 33 kV at instance 4. It can be seen from Figure 1 (c) that the highest AC breakdown voltage of the PFAE-based nanofluid containing 0.01, 0.02 and 0.03 % Fe3O4 nanoparticles prepared using Method II is 32, 38 and 35 kV, respectively, whereas the lowest AC breakdown voltage is 8, 17 and 15 kV, respectively.

3.2. Data Analysis

Figure 2 (a) shows the two-parameter Weibull plot of the virgin PFAE oil and PFAE-based nanofluid prepared using Method I and Figure 2 (b) shows the two-parameter Weibull plot of the PFAE-based nanofluids prepared using Method II. The AC breakdown voltage data for the virgin PFAE oil are also superposed in Figure 2 (a) and (b) as reference. Table 2 shows the values of the shape parameter, scale parameter and correlation coefficient for the virgin PFAE oil, PFAE-based nanofluids prepared using Method I and Method II based on the two-parameter Weibull plots in Figures 2 (a) and (b). It can be seen from the Table 2 that the correlation coefficient for each sample is close to 1 suggesting there is a strong, positive correlation between the Weibull probability and AC breakdown voltage. Based on the linear lines in Figures 7 (a) and (b), the shape parameter, β for the virgin PFAE oil and PFAE-based nanofluid with a Fe_3O_4 nanoparticle concentration of 0.01 g/l, 0.01 %, 0.02 % and 0.03 % is 4.78, 4.47, 6.53 and 7.03 respectively. The shape parameter indeed affects the shape of the Weibull plots. The population of $\beta < 1$ exhibit a probability that decrease with the AC breakdown voltage, the population of $\beta = 1$ have a constant probability and the population of $\beta > 1$ have a probability that increase with the AC breakdown voltage. Table 3 shows the AC breakdown voltage for the virgin PFAE oil and PFAE-based nanofluids prepared using Method I and Method II based on the Weibull probabilities of Figures 7 (a) and (b). Based on the Weibull probability of 63.2%, the AC breakdown voltage is the lowest for the PFAE-based nanofluid containing 0.01% Fe_3O_4 nanoparticles compared to other samples, with a value of 17.45 kV. In contrast, the AC breakdown voltage is the highest for the PFAE-based nanofluid prepared using Method II containing 0.02% Fe_3O_4 nanoparticles, with a value of 30.35 kV. Interestingly, even a slight increase in the Fe_3O_4 nanoparticle concentration has a dramatic effect on the AC breakdown voltage of the PFAE-based nanofluid.



(a) (b)

(c)

Figure 1. Distribution of the AC breakdown voltage for (a) the virgin PFAE oil, (b) the PFAE-based nanofluid prepared using Method I., and (c) the PFAE-based nanofluids prepared using Method II

Table 2. Shape parameter, scale parameter and correlation coefficient obtained from the two-parameter weibull plots for virgin oil and pfae-based nanofluids prepared using method I and method II

Parameter	Virgin PFAE oil	PFAE-based nanofluid (Method I)	PFAE-based nanofluids (Method II)		
		0.01 g/l Fe_3O_4	0.01% Fe_3O_4	0.02% Fe_3O_4	0.03% Fe_3O_4
β	4.78	4.47	3.38	6.53	7.02
η	19.26	23.84	17.45	30.35	27.14
ρ	0.96	0.99	0.93	0.97	0.97

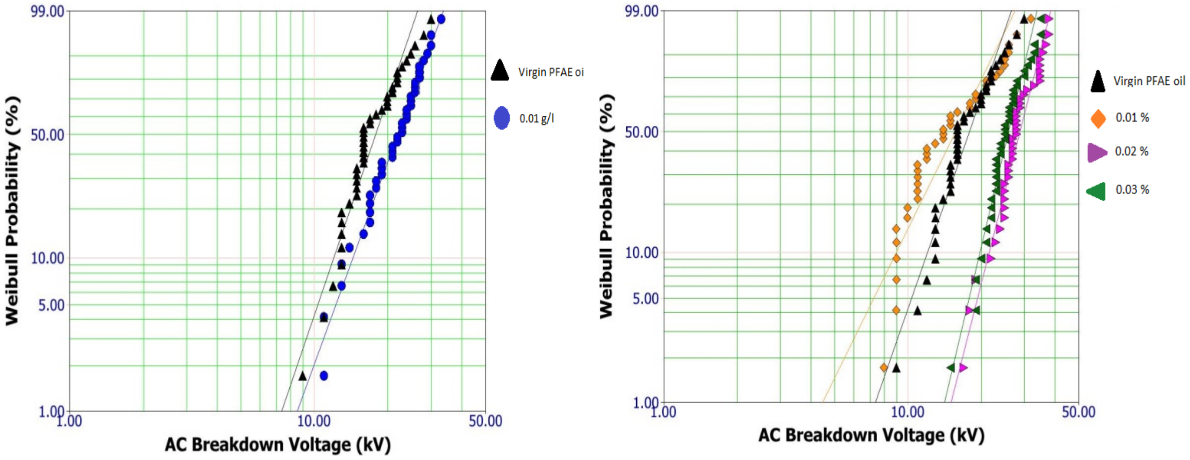
Table 3. Weibull probability for AC breakdown voltage of all samples based on the two-parameter weibull

Weibull probability (%)	AC breakdown voltage (kV)				
	Virgin PFAE oil	PFAE-based nanofluid (Method I)	PFAE-based nanofluids (Method II)		
		0.01 g/l Fe_3O_4	0.01% Fe_3O_4	0.02% Fe_3O_4	0.03% Fe_3O_4
1	7.36	8.52	4.48	15.00	14.10
5	10.34	12.26	7.24	19.26	17.78
10	12.03	14.41	8.97	21.50	19.70
50	17.84	21.97	15.66	28.70	25.76
63.2	19.26	23.84	17.45	30.35	27.14

It appears that a proper percentage of Fe_3O_4 is important to achieve the highest improvement in the AC breakdown voltage level. The addition of 0.01 g/l of Fe_3O_4 nanoparticles into the PFAE oil increases its AC breakdown voltage by 23.8%. This is obvious when the addition of 0.02% Fe_3O_4 nanoparticles into the PFAE oil increase the AC breakdown voltage by 57.6% at a Weibull probability of 63.2%. However, a further increase in the amount of Fe_3O_4 (0.03%) would see a bit reduction in the improvement of breakdown voltage level.

The conductive nanoparticles act as electron scavengers in the insulation oil under electrical stresses, which is convert the fast electrons into slow negatively charged particles [14],[25]. In other words, it takes a long time for the streamer process to breakdown under electrical stress. Figure 3 shows an illustration of the streamer process for the insulation oil with and without conductive nanoparticles. It can be seen that the streamer is in direct contact between the high voltage electrode and ground for the insulation oil without conductive nanoparticles and therefore, the streamer takes a shorter time to breakdown. In contrast, the streamer takes a longer time to breakdown for the insulation oil with conductive nanoparticles upon application of high voltage because of electron scavenger action.

Figure 4 shows the effect of Fe_3O_4 nanoparticle concentration on the AC breakdown voltage of the PFAE-based nanofluid at a Weibull probability of 63.2%. It can be seen that the addition of 0.01% Fe_3O_4 nanoparticles into the PFAE oil decreases the AC breakdown voltage, which contradicts what is initially expected in this study. Different concentrations of nanoparticles have been used in previous studies [13], [26],[27] the results show that some concentrations do not improve the AC breakdown voltage of the dielectric liquid. Indeed, the results of this study indicate that 0.01% is not the ideal Fe_3O_4 nanoparticle concentration for PFAE-based nanofluids.



(a) (b)

Figure 2. Two-parameter Weibull plot of the AC breakdown voltage for (a) the virgin PFAE oil and PFAE-based nanofluid prepared using Method I, and (b) the virgin PFAE oil and PFAE-based nanofluid prepared using Method II

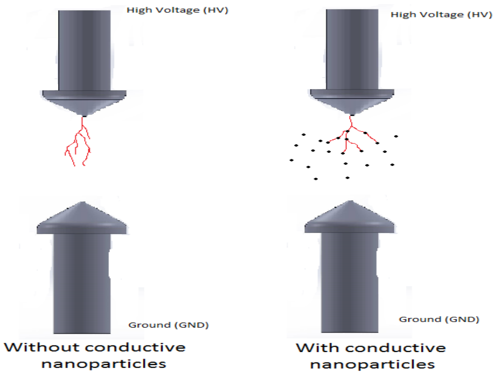


Figure 3. Illustration of streamer process in insulation oil with and without conductive nanoparticles

4. CONCLUSION

The AC breakdown voltage of PFAE oils mixed with Fe_3O_4 nanoparticles at different concentrations has been investigated in this study. Two methods are used to prepare the PFAE-based nanofluids, namely Method I and Method II. Method I is based on the weight of the nanoparticles whereby the PFAE-based nanofluid is prepared by mixing the PFAE oil with 0.01 g/l of Fe_3O_4 nanoparticles. Method II is based on the volume fraction of the nanoparticles, whereby the PFAE-based nanofluids are prepared by mixing the PFAE oil at three different concentrations of Fe_3O_4 nanoparticles (0.01, 0.02 and 0.03%). The PFAE-based nanofluids are mixed using a laboratory homogenizer to ensure that the nanoparticles are well-dispersed in the PFAE oils. The results are analysed using Weibull statistical analysis and it is found that there is enhancement in the AC breakdown voltage of the PFAE-based nanofluids with the exception of one sample prepared using Method II (containing 0.01% Fe_3O_4 nanoparticles). The presence of Fe_3O_4 nanoparticles slows down the streamer process in the PFAE oil due to the electron scavenger action.

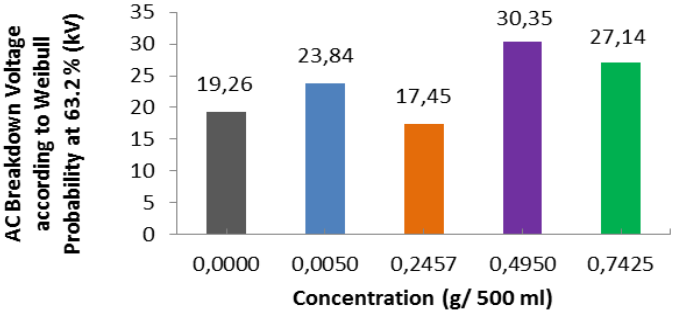


Figure 4. Effect of Fe_3O_4 nanoparticle concentration on the AC breakdown voltage of PFAE-based nanofluids at a Weibull probability of 63.2%

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