International Journal of Scientific Engineering and Research (IJSER)
www.ijser.in
ISSN (Online): 2347-3878
Volume 2 Issue 4, April 2014

Breakdown Voltage Characteristics of Castor Oil as Alternative to Transformer Insulation Oil

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Abstract: ***Suitability of non-edible oil as a replacement for mineral oil in power transformer has been a major research concern in product analysis and development. However, there is paucity of information in literature on the suitability of castor oil as alternative transformer insulation oil. This study examined the suitability of castor oil as alternative transformer insulation oil. Four castor oil samples were collected from University of Agriculture, Abeokuta and five experimental tests on alternating current (a.c.) breakdown voltage were carried out on each of the castor oil samples. Temperature range of between 27^{o}C and 37^{o}C was adopted for the study that was carried out in both rainy (July) and dry (December) seasons. A Baur DPA75 was used to measure the a.c. breakdown voltage. The results of a.c. breakdown voltage measurements of castor oil for July at temperatures of 27^{o}C and 32^{o}C were 23.8 kV and 24.2 kV respectively and similar values for December at 30^{o}C and 37^{o}C were 23.9 kV and 24.1 kV respectively. The average breakdown voltage for the two months was 24.0475 kV which is less than 25 kV the minimum standard value for both 11/0.415 kV and 33/0.415 kV transformer insulation oil. This study showed that raw castor oil is not suitable for both 11/0.415 kV and 33/0.415 kV transformer insulation oil.***

Keywords: Breakdown voltage, Castor oil, Ester, Mineral insulation oil, Power Transmission, Transformer

1. Introduction

With the worldwide growing demand for electrical energy, environmental and safety concerns cannot be neglected. Power transformers being crucial elements in electric power transmission network also have to follow this trend. For more than one century, power transformers are filled with mineral oil serving as a heat transfer and insulating medium [1]. Nowadays significant efforts are aimed in quest for a more environmentally friendly replacement of this petroleum-based product. Natural esters or vegetable oils, refined from plant materials are gaining attention in recent times as alternatives. They are nontoxic, more biodegradable and less flammable than mineral oils [4].

Ester-based transformer oils have gained the success in distribution transformers in certain countries and regions like Brazil, United State of America and Asian countries and they are currently under research and development for application in large power transformers. Ester oils are advantageous compared to traditional mineral oil as these oils are less flammable, non-toxic and more biodegradable. A number of vegetable oils such as sunflower, canola and rapeseed have been tested and found suitable [7]. However, not much has been found in the literature on suitability of non-edible oil such as castor oil as suitable transformer insulation oil.

A typical vegetable oil for consideration as alternative ester-based transformer insulation oil is Castor oil. It is pale amber viscous liquid derived from the seeds of the plant *Ricinus Communis*, sometimes known as *ricinus oil*. Castor oil is one of the few naturally occurring glycerides that approach being a pure compound, since the fatty acid portion is nearly nine-tenths *ricinoleic* [2]. Castor oil is a vegetable oil obtained from the castor bean. Castor oil is a colourless to very pale yellow liquid with mild or no odor or taste. Its boiling point is 313 °C (595 °F) and its density is 961kg/m^3. It is a triglyceride in which approximately between 87% and 90% of fatty acid chains are ricinoleic acid. Oleic and linoleic acids are the other significant components.

Figure 1: Castor beans [3]

2. Experimentation

The castor beans undergo various processing in the course of its preparation for extraction as reported in reference [3]. The unit operations involved cleaning, drying, winnowing and grinding. Extracted samples of castor oil were sourced from the University of Agriculture, Abeokuta. The suitability of castor oil as alternative transformer insulation oil was investigated. To achieve this, test on electric property was carried out on castor oil as well as mineral oil at different days and varying temperature of the day. Tests were carried out for alternating current (a.c) breakdown voltage.

The original physical and chemical properties of transformer oil changed when subjected to electrical and mechanical

stresses while in operation. The experimental results of the physical properties of castor oil obtained in reference [3] are given in Table 1.0. The results show that it has the same physical properties with transformer insulation oils. Therefore, this oil must be tested to ascertain its electrical properties before being recommended as transformer insulation oil.

Table 1: Physical Properties of Castor Oil.

Properties	*Values*
Flash point	229^{o}C
Density @ 25^{0}C	0.96g/cm^{3}
Boiling point	313^{o}C
Melting point	-10^{o}C
Solubility in water	Not soluble

Source: [3].

A Baur DPA75 was used for a.c. breakdown voltage measurements as per ASTM D1816 with partial sphere electrodes and 1mm gap. In total 4 samples of 5 breakdowns were taken to give 20 breakdown voltages in total. This experiment was carried out in two seasons (dry and rain seasons). Care was taken to allow sufficient time for air bubbles to be expelled when pouring castor oil into the test cell. It is noted that ASTM D1816 has not been verified for oils over 19cSt at 40°C viscosity, and that esters are more viscous, however it has been reported that this standard is suitable with a 15 minutes standard time after pouring to give the bubbles of air sufficient time to escape. Typical instrumentation used (Electrode for measuring the breakdown voltage of liquid insulation) is shown in Fig.2.0.

The breakdown voltage is measured on-site following the test sequence [6]:

(i) In the vessel, two standard-compliant test electrodes with a typical clearance of 1mm are surrounded by the insulating oil.
(ii) During the test, a test voltage is applied to the electrodes. The test voltage is continuously increased up to the breakdown voltage with a constant slew rate of 2 kV/s.
(iii) Breakdown occurs in an electric arc, leading to a collapse of the test voltage.
(iv) Immediately after ignition of the arc, the test voltage is switched off automatically.
(v) Ultra fast switch off is crucial, as the energy that is brought into the oil and is burning it during the breakdown, must be limited to keep the additional pollution by carbonization as low as possible.
(vi) The root mean square value of the test voltage is measured at the very instant of the breakdown and is recorded as the breakdown voltage.
(vii) After the test is completed, the insulating oil is stirred automatically and the test sequence is performed repeatedly.
(viii) The resulting breakdown voltage is calculated as mean value of the individual measurements.

The calculated mean value of breakdown voltage was thereafter checked against standard values for transformer oil properties for different transformer ratings as recommended by the IEE Guide for reclamation of Insulating Oil and Criteria for Its Use (IEE Std 637-1985) and British standard BTA4705. The recommended ratings in respect of breakdown voltage as reported in reference [1] are as follows:

(i) For the 11/0.415 kV step down transformer, the minimum breakdown voltage of its insulating oil should not be less than 25 kV; and
(ii) For 33/0.415 kV step down transformer, the minimum breakdown voltage of its insulating oil should not be less than 45 kV.

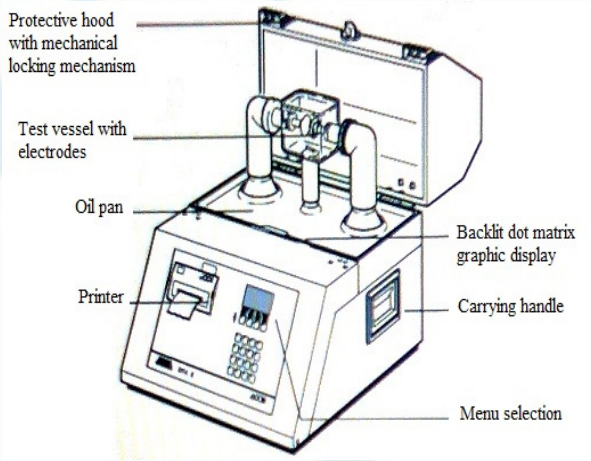

Figure 2: Electrode for measuring the breakdown voltage of liquid insulation [5].

3. Experimental Result and Discussion

The dielectric breakdown voltage is a measurement of electrical stress that insulating oil can withstand without failure. It is measured by applying a voltage between two electrodes under prescribed conditions under the oil. The dielectric test measures the voltage at which the oil breaks down, which is indicative of the amount of contaminant (usually moisture) in the oil. From Table 2.0, results for alternating current (a.c.) breakdown voltage of castor oil samples reported were obtained in the rainy season from four different samples (R1, R2, R3 and R4). These measurements were taken in the month of July, 2011. Five (5) breakdown experiments were performed for each of the samples resulting in a total of twenty (20) breakdown trials replicated twice in a day. This gives 20 daily mean measurements of breakdown voltage.

The twenty (20) breakdown voltage trials, which were replicated twice in a day, are graphically described in Fig. 3.0. From Fig. 3.0, it can be seen that the breakdown voltage of castor oil measured at 27^{o}C was between 24.0 kV and 24.6 kV, while the measurement at 32^{o}C ranged between 23.6 kV to 24.2 kV. It was observed that the values obtained at 27^{o}C, at lower temperature, was slightly higher than the values obtained at 32^{o}C when the temperature was relatively higher. This showed that the breakdown voltage measurement was slightly influenced by temperature.

International Journal of Scientific Engineering and Research (IJSER)
www.ijser.in
ISSN (Online): 2347-3878
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The daily mean measurements of breakdown voltage recorded for rain season in Table 2.0 are graphically presented in Fig. 4.0. The distribution shows a range of breakdown voltage between 23.8 kV and 24.2 kV. Through statistical analysis, this gives a mean value of 24.055 kV. This value is less than the minimum required for the raw castor oil to be suitable for use as transformer insulating oil in either 11/0.415 kV transformer or 33/0.415 kV transformer, when compared with the standards reported in reference [1].

Table 2: Results for a.c. Breakdown Voltage of Castor oil samples R1-R4 (July, 2011)

Breakdown Trials (Tests)	*Raw Castor Oil Sample*	*Breakdown Voltage(kV) (27^oC)*	*Breakdown Voltage(kV) (32^oC)*	*Breakdown Voltage(kV) (daily mean)*
BDT1	R1	24.60	23.80	24.20
BDT2	R1	24.20	24.00	24.10
BDT3	R1	24.00	24.00	24.00
BDT4	R1	24.20	24.20	24.20
BDT5	R1	24.20	24.00	24.10
BDT6	R2	24.00	24.00	24.00
BDT7	R2	24.20	24.00	24.10
BDT8	R2	24.40	23.80	24.10
BDT9	R2	24.00	24.00	24.00
BDT10	R2	24.20	24.00	24.10
BDT11	R3	24.00	23.60	23.80
BDT12	R3	24.20	23.80	24.00
BDT13	R3	24.20	23.80	24.00
BDT14	R3	24.20	23.80	24.00
BDT15	R3	24.40	23.80	24.10
BDT16	R4	24.00	24.00	24.00
BDT17	R4	24.20	24.00	24.10
BDT18	R4	24.00	24.00	24.00
BDT19	R4	24.20	24.00	24.10
BDT20	R4	24.40	23.80	24.10

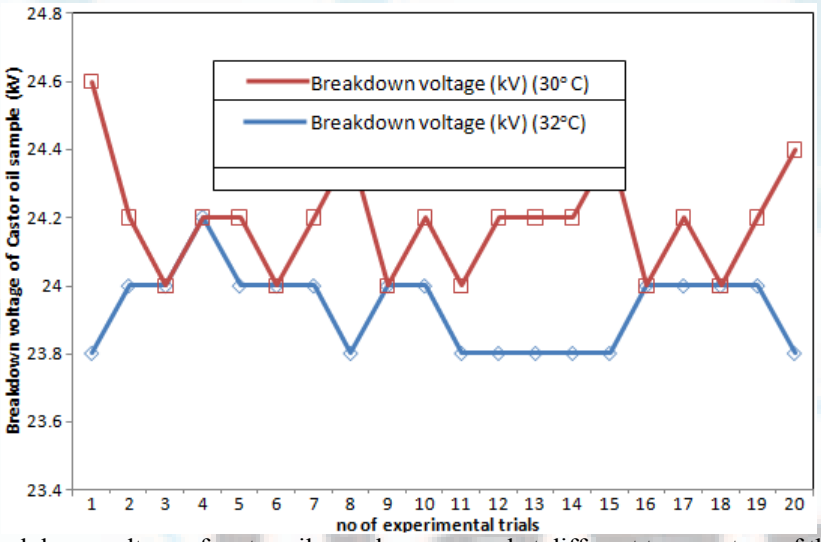

Figure 3: Dielectric breakdown voltage of castor oil samples measured at different temperature of the day during the rainy season.

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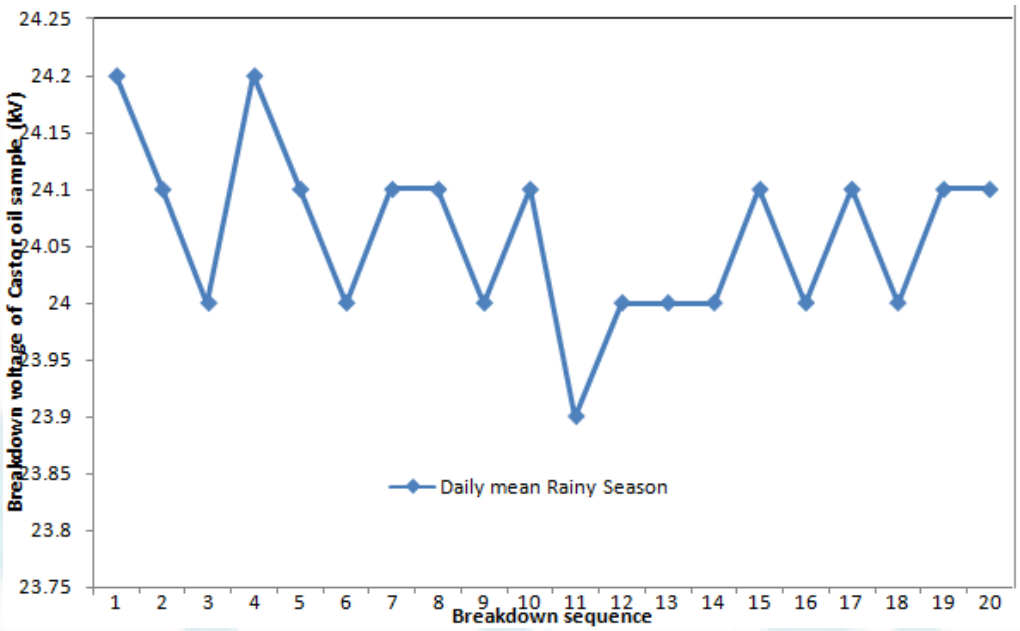

Figure 4: Average dielectric breakdown voltage of castor oil samples measured during the rainy season

Similarly from Table 3.0, results for a.c. breakdown voltage of castor oil samples reported were obtained in the dry season from four different samples (D1, D2, D3 and D4). These measurements were taken in the month of December, 2011. Five (5) breakdown experiments were performed for each of the samples resulting in a total of twenty (20) breakdown trials replicated twice in a day (at 30°C and 37°C). This gives 20 daily mean measurements of breakdown voltage.

The twenty (20) breakdown voltage trials, which were replicated twice in a day, are graphically described in Fig. 5.0. From Fig. 5.0, it was observed that the breakdown voltage of castor oil measured at 30°C ranged between 24.0 kV and 24.2 kV, while the measurement at 37°C ranged between 23.8 kV to 24.2 kV. It can be seen that the values obtained at 30°C, at a lower temperature, was very slightly higher than the values obtained at 37°C when the temperature was relatively higher. This showed that the breakdown voltage measurement was slightly influenced by temperature. It was however noted that the effect was not as relatively profound as the case obtained earlier for the rainy season. This may be apparently attributed to the generally high temperature during the dry season.

Fig. 5.0 clearly showed at least eight cases of super-imposition of values of breakdown voltage of castor oil measured at 30°C and 37°C. This further showed, for measurements in the dry season, that the effect of temperature was not as significant in relative terms as the case obtained earlier for the rainy season. The daily mean measurements of breakdown voltage recorded for dry season in Table 3.0 are graphically presented in Fig. 6.0. The distribution shows a range of breakdown voltage between 23.9 kV and 24.1 kV. Through statistical analysis, this gives a mean value of 24.035 kV. This value is also less than the minimum required for the raw castor oil to be suitable for use as transformer insulating oil either in the 11/0.415 kV or 33/0.415 kV transformer, when compared with the standards reported in the literatures [1].

Table 3: Results for a.c Breakdown Voltage of Castor oil samples D1-D4 (December, 2011)

Breakdown Trials (Tests)	*Raw Castor Oil Sample*	*Breakdown Voltage(kV) (at 30°C)*	*Breakdown Voltage(kV) (at 37°C)*	*Breakdown Voltage(kV) (daily mean)*
BDT1	D1	24.00	24.20	24.10
BDT2	D1	24.10	23.90	24.00
BDT3	D1	24.00	24.00	24.00
BDT4	D1	24.20	24.00	24.10
BDT5	D1	24.10	23.90	24.00
BDT6	D2	24.00	24.00	24.00
BDT7	D2	24.10	24.10	24.10
BDT8	D2	24.10	23.90	24.00
BDT9	D2	24.20	24.00	24.10
BDT10	D2	24.10	23.90	24.00
BDT11	D3	24.00	24.00	24.00
BDT12	D3	24.00	24.00	24.00
BDT13	D3	24.20	24.00	24.10
BDT14	D3	24.00	23.80	23.90
BDT15	D3	24.10	23.90	24.00
BDT16	D4	24.20	24.00	24.10
BDT17	D4	24.10	24.10	24.10
BDT18	D4	24.00	24.00	24.00
BDT19	D4	24.10	24.10	24.10
BDT20	D4	24.10	23.90	24.00

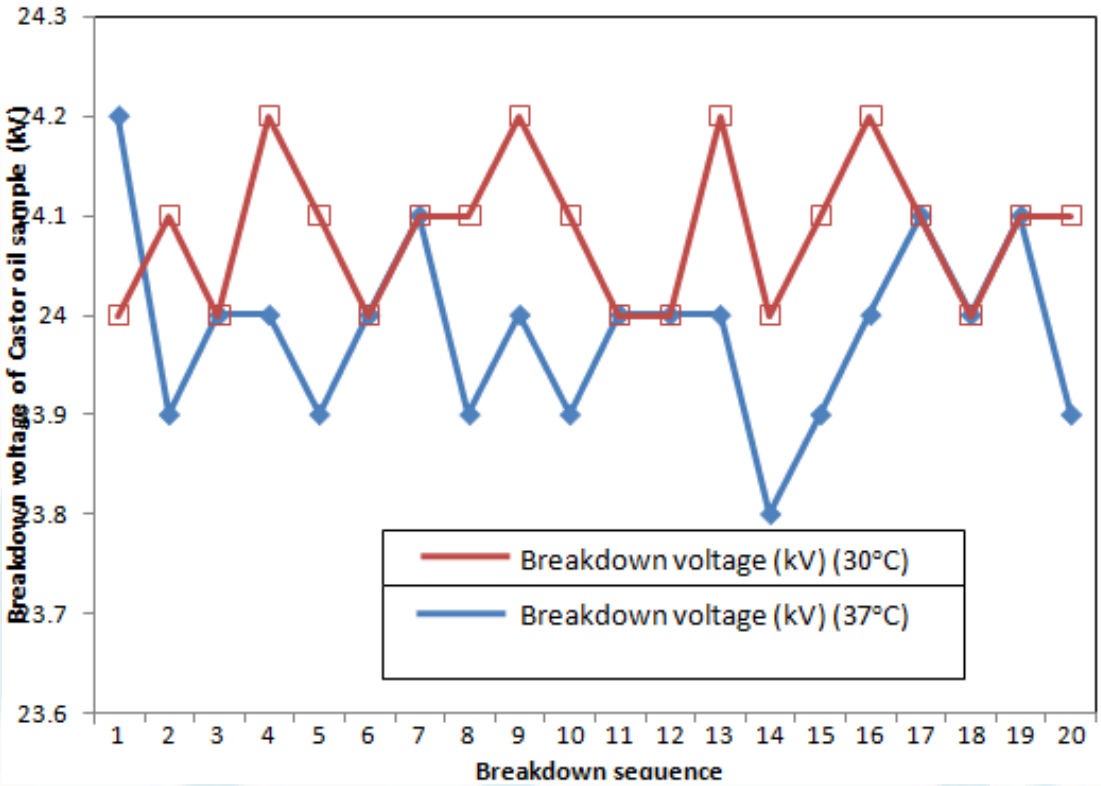

Figure 5: Dielectric Breakdown voltage of castor oil samples measured at different temperature of the day during the dry season.

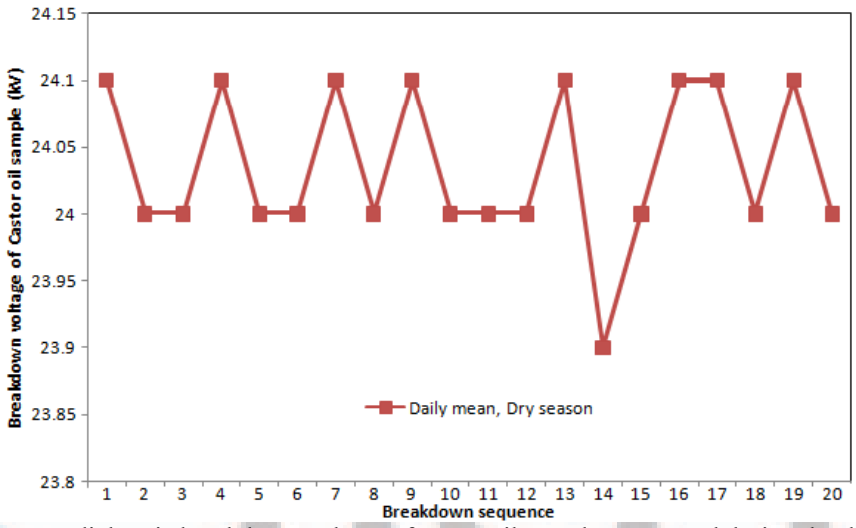

Figure 6: Mean dielectric breakdown voltage of castor oil samples measured during the dry season.

Results of the daily mean measurements of breakdown voltage recorded for rainy and dry season in Tables 2.0 and 3.0 are graphically presented in Fig. 7.0. From the twenty (20) mean breakdown voltage values in each case, as shown in Fig. 7.0, it was observed that the mean breakdown voltage of castor oil measured in the rainy season ranged between 23.8 kV and 24.2 kV, while the values in the dry season ranged between 23.9 kV and 24.1 kV. From Fig. 7.0, six cases of super-imposition of values of breakdown voltage of castor oil measured in the two seasons are evident. It can thus be inferred, for measurements in the two seasons, that seasonal variation in the values obtained was not significant.

However, a close observation of the combined mean of the breakdown voltage recorded for both seasons in Fig. 8.0 showed a minimum and maximum value of 23.95 kV and 24.15 kV. The distribution yielded a mean breakdown voltage of 24.0475 kV.

4. Comparison with Standard values for different Transformer ratings

The mean breakdown voltage of 24.0475 kV obtained for castor oil is, on the one hand, less than the minimum required for the raw castor oil to be suitable for use as transformer insulating oil in the 33/0.415kV transformer as recommended by the IEEE Guide for reclamation of Insulating Oil and Criteria for Its Use (IEE Std 637-1985) and British standard BTA4705. The minimum breakdown

voltage of transformer insulating oil should not be less than 45kV for 33/0.415 kV transformer [1]. The gap is so wide that the raw castor oil cannot be recommended for use in 33/0.415 kV transformer.

On the other hand, the mean breakdown voltage of 24.0475 kV obtained for castor oil is also less than the minimum required for the raw castor oil to be suitable for use as transformer insulating oil in the 11/0.415 kV transformer as recommended by the IEE Guide for reclamation of Insulating Oil and Criteria for Its Use (IEE Std 637-1985) and British standard BTA4705. In this case, the minimum breakdown voltage of transformer insulating oil should not be less than 25 kV for 11/0.415 kV transformer [1]. The comparison is illustrated in Fig. 9.0.

It was observed from Fig. 9.0 that the breakdown voltage of 24.0475 kV obtained for castor oil is very close to the requirement for use in the 11/0.415 kV transformer. The slight difference may be due to impurities or other form of contamination in the raw castor oil.

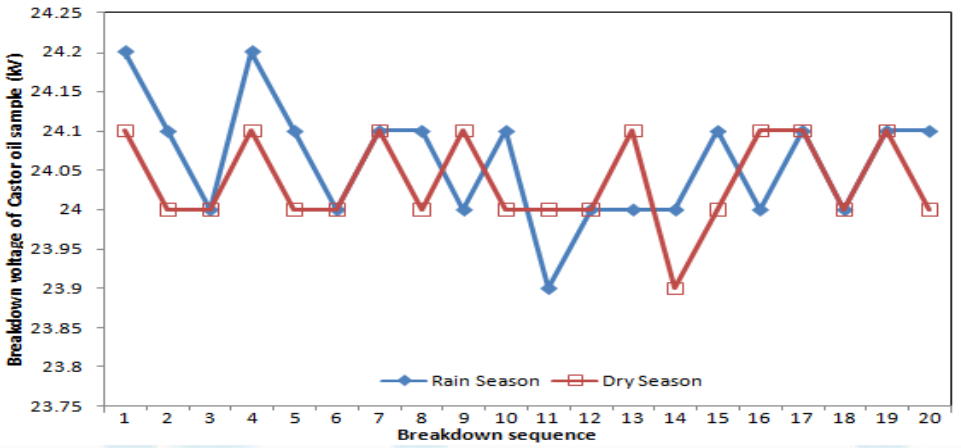

Figure 7: Dielectric Breakdown voltage of castor oil samples measured during the rain and dry season

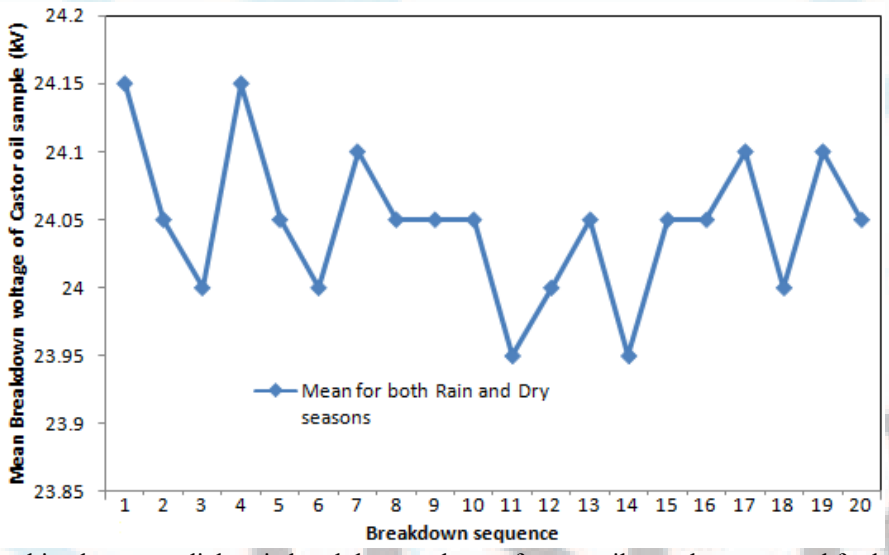

Figure 8: Combined average dielectric breakdown voltage of castor oil samples measured for both seasons.

International Journal of Scientific Engineering and Research (IJSER)
www.ijser.in
ISSN (Online): 2347-3878
Volume 2 Issue 4, April 2014

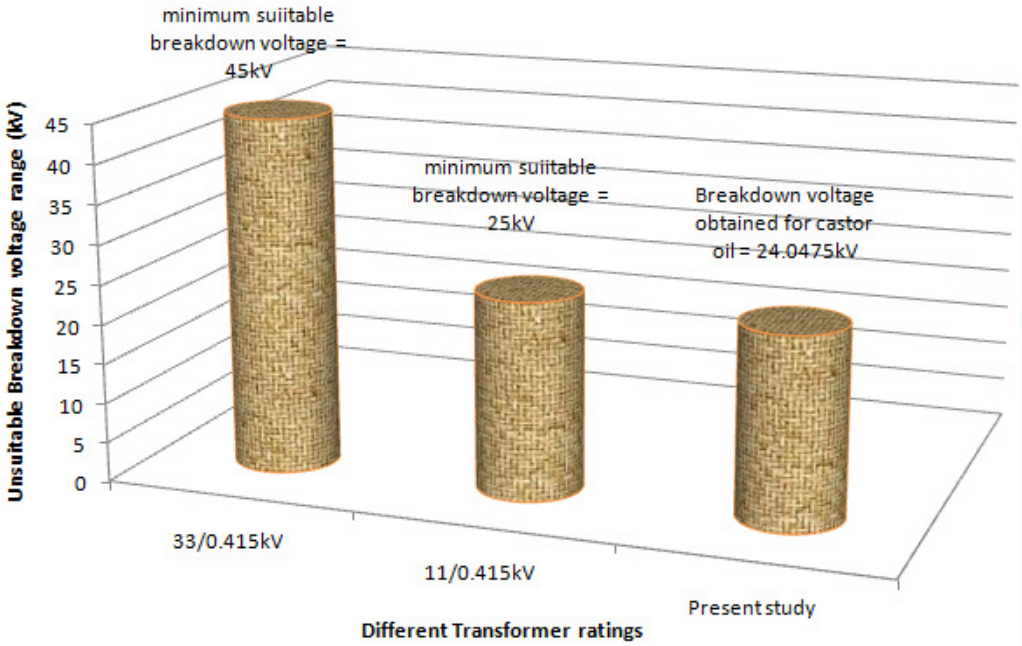

Figure 9: Comparison of results of dielectric breakdown voltage of castor oil with standard requirements for different Transformer ratings.

5. Conclusion

This study was undertaken to confirm or otherwise, the suitability of castor oil as suitable transformer insulation oil. From the results obtained, the following conclusions can be drawn:

(i) The breakdown voltage measurement was slightly influenced by temperature, especially during the rainy season.
(ii) The mean breakdown voltage of 24.0475 kV obtained for castor oil is less than the minimum required for the raw castor oil to be suitable for use as transformer insulating oil in the 33/0.415 kV transformer. It is also less than the minimum required for the raw castor oil to be suitable for use as transformer insulating oil in the 11/0.415 kV transformer.
(iii) The above findings from this study suggest that raw castor oil is unsuitable for use as transformer insulating oil.
(iv) Part of the findings from this work revealed that the breakdown voltage of 24.0475 kV obtained for raw castor oil is very close to the requirement for use in the 11/0.415 kV transformer; the slight difference being attributed to possibility of impurities or other form of contamination in the raw castor oil.

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