Physical Sciences Section

Pak. j. sci. ind. res., vol. 35, no. 10, October 1992

STUDY OF CABLE OIL AND PAPER OIL COMPOSITE SAMPLES DOPED WITH ADDITIVES UNDER HIGH ELECTRICAL STRESS

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(Received February 22, 1992; revised October 15, 1992)

The effects of aromatic additives have been investigated on the performance of mineral cable oil used in 132kV paper insulated underground cable in service in Riyadh area. Samples containing different concentrations of these additives were used and evaluation made on conduction current, burst current and breakdown voltage. Virgin samples of the dielectric paper used in this cable were impregnated in these oil samples for the investigation of power factor and breakdown voltage. The results indicate that an optimum concentration of the additives improves the performance of liquid as well as the paper-liquid composite.

Key words: Aromatic additives, Cable oil, Paper oil, High electric stress.

Introduction

Inspite of advent of new materials like plastics, the oil impregnated paper is still a cheaper form of practical high voltage insulation which can be easily adopted for various applications like bushings transformers and cables etc. It is preferred because of its high operating stress, low dielectric loss and a slow rate of deterioration in service.

Although a tremendous amount of data on the breakdown strength and conduction is available in literature for the impregnating insulating liquids, yet, there is dearth of information on the behaviour of liquid-paper composite. Insulating liquids exhibit a marked improvement in their characteristics by the addition of trace amounts of aromatic hydrocarbons. Angerer [1] has shown that aromatic additives either quench the formation of hydrogen gas that is produced as a result of rupture of carbon- hydrogen bonds or they tend to absorb it if it is released. It has also been reported that there exists an optimum concentration of additive [1,2] which absorbs or prevents formation of gas, whereas excess of the concentration causes an accelerated dissociation of oil molecules. Behaviour of additives in cable oils and its composite with paper is not well documented. Moreover, it should also be interesting to study the behaviour of pulse current which appears superimposed on conduction current in the presence of such additive. Such a study is likely to improve our understanding of fundamental processes involved in the breakdown of insulation.

This paper describes the measurement of conduction and burst current in cable oil doped with 1-methylenepthelene (MN) and benzophenon (BP) in various concentrations. It also shows the impact of these additives on the permittivity and tanδ for oil as well as its composite with kraft paper that is used in 132 kV high voltage cable, currently in service in Riyadh region of Saudi Arabia.

Experimental

Oil sample preparation. Mineral cable oil was dehydrated by passing through a one meter long chromatograph column filled with non-adosrbent silicagel crystals and then filtered under vacuum by passing it over (10-16 μm) porosity sintered glass filter. 1- Methylenepthalene ($C_{10}H_7.CH_3$) and benzophenon $(C_6H_5)_2.CO$) were used as aromatic additives and by doping the fresh cable oil with precise amounts of these additives, oil samples of 0.001, 0.005, 0.01 and 0.05 molar concentrations were prepared.

Oil-paper sample preparation. A single layer of paper having an average thickness of 110 μm and a density of 1.2 gm/cm^3 was cut into 6 x 6 cm square pieces and placed on the sample trays containing oil samples with different additive concentrations. To keep the test sample flat in the tray while the vacuum treatment was carried out, a glass disk was laid on top of the test sample. These trays were arranged in the vacuum chamber as shown in Fig. 1, and kept for 48 hr. under a vacuum of around 5 Pa and were considered fully impregnated. All

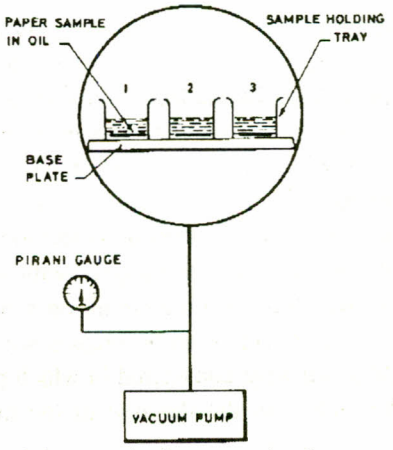

Fig. 1. Sample impregnation in vacuum chamber.

subsequent tests on these samples were carried out at atmospheric pressure.

Conduction current measurement. For this purpose, non-uniform electrode configuration was used. The plane electrode was made of brass 25.4 mm in diameter and 10 mm thick, with rounded edges. The point electrode (the cathode) was a steel sewing needle of tip radius 100 μm. The test cell and the electrode assembly were washed thoroughly every time the electrode or oil was replaced with petroleum ether and then immersed in petroleum spirit (68°) and subjected to the ultrasonic energy for 30 min. After cleaning, the test cell was dried inside an evacuated desiccator containing silicagel for about 15 min.

The oil after pouring into the cell was left for 1 hr. to stabilize before application of the stress. Figure 2 shows the schematic diagram for the experimental setup of conduction current test. The electrode gap was fixed at 1.5 mm and a negative high field was applied to the point electrode not exceeding 80% of the dielectric strength of the oil gap.

Every possible measure and precautions were taken to minimize leakage current and interfering signals using shielded enclosure, cables and proper grounding. Before each measurement, the sample was conditioned by short circuiting and grounding the electrodes for about 60 sec., so as to eliminate possible space charges from the system or to remove the incluence of the preceeding experiment. Conduction current was then recorded for 600 sec. duration after the application of voltage for each experimental run.

ε_r and tanδ measurement. A precision power frequency schering bridge (Tettex type 2821) was used for the measurements of relative permittivity and tanδ. Three terminal test cell Tettex type 2903 was used for liquid sample measurements. Whereas Tettex test cell type 2904 was used for impregnated paper samples and measurements were carried out at 20N/cm^2 pressure.

Breakdown voltage measurement of impregnated paper. For this purpose as test cell was specially fabricated as shown in Fig. 3. To keep the uniformity of the stress, the weight of high voltage brass electrode exerts a pressure of around 0.1 N/cm^2 on the sample. The impregnated paper samples were immersed in the same oil sample in which they were impregnated. Tests were performed using a 2.5 KVA; 0-50 kV, 60 Hz noise free transformer as the source of high voltage supply and the setup was equipped with an automatic tripping device which opened the circuit on a sudden large flow of current in the event of sample breakdown. Only those values of breakdown were considered in which paper punctured near the middle of the flat part of the high voltage electrode.

Results and Discussion

Effect of additives on conduction current. Figure 4 depicts results of variation of quasi-steady conduction current 'i' in fresh cable oil in the time period 't' varying from 10-600 s after the application of stress. The magnitude of 'i' decreases with time after the application of stress. Generally i-t characteristic obeys power law as $i=kt^n$, where k is the constant which depends on experimental parameters and 'n' is the gradient. In liquid insulation such a behaviour of conduction current is well known and is attributed to 'conditioning' effect [3,4]. The magnitude of quasi-steady conduction current increases with the increase in voltage, but near the breakdown level this power law fails and the current increases sharply. As the stress level increases beyond certain limit, the enhanced field emission causes dissociation of liquid molecules which increases

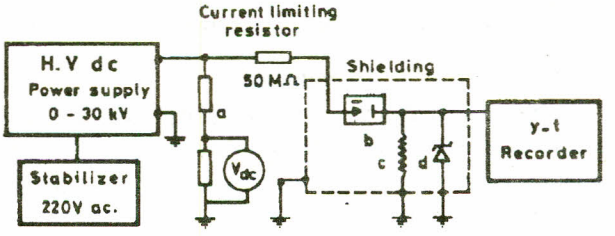

Fig. 2. Experimental setup for conduction current test. (a) Voltage divider (1000:1), (b) Test cell, (c) Detection resistor (10 k), (d) Surge suppressor (6.1 Volt)

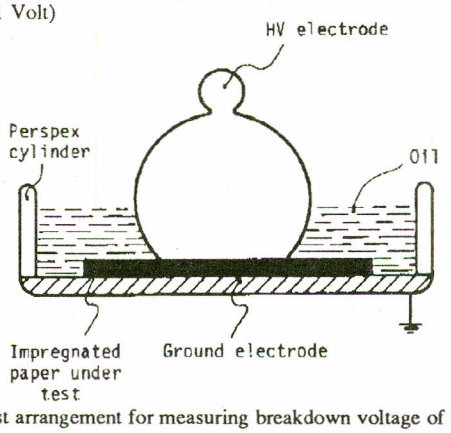

Fig. 3. Test arrangement for measuring breakdown voltage of impregnated paper sheets.

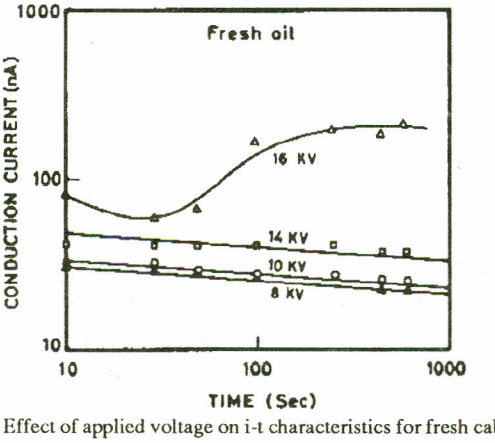

Fig. 4. Effect of applied voltage on i-t characteristics for fresh cable oil.

both the content of charge carriers as well as their mobility and hence the current is also increased [3].

Figure 5 and 6 shows the effect of various concentrations of MN and BP respectively on the i-t characteristics at 12 kV. It is clear that addition of trace amounts of additives render the oil to behave in a different fashion, since 0.001 M concentration of both additives causes a considerable reduction in 'i'. But its level starts increasing with the addition in the molar concentration of both additives. This indicates that upto a certain concentration the additive molecules form a negative space charge in the vicinity of cathode thus reducing the local field. But when the additive concentration is increased further the corresponding increase in current level suggests that excess molecules of additive either become source of charge carriers or liquid's ion drift velocity has increased. It may be that both mechanisms are operative simultaneously. Sakamoto and Usuda [5] have shown that with the addition of trace amounts of electronegative substances in transformer oil, the ion drift velocity with which they leave the electrode reduces with the increase in additive concentration and reaches a minimum at an optimum value, but again increases appreciably as concentration exceeds this optimum.

It is also clear from both of these figures that 0.005 M concentration of both additives is the critical value beyond which the trend reverses, since the conduction current level starts declining appreciably with a further increase in concentration. This is warranted as the negative space charge due to addition of charge carriers increases with the increase in additive concentration. It may be perceived that when space charge volume extends deep down the interelectrode gap, then presence of its outer front (at the axis of electroe gap) in the vicinity of anode will enhance anode field and result in the production of a strong opposite space charge which will neutralize it's bulk effect thus reducing its size and hence the conduction current.

Figure 7 demonstrates the effect of voltage on current magnitude. It is clear that almost monotonic trend of variation of 'i' with additive concentration holds in a voltage range of 8–16 kV. For the sake of comparison and clarity in these curves, the magnitudes of current are taken at the instant of 10 s after the application of stress and are plotted against molar concentration of MN in oil. It is interesting to note that even the presence of BP in this mineral oil displays almost similar behaviour in the same voltage range as shown in Fig. 8, except that current magnitude in BP doped samples is comparatively smaller at all voltage levels. Both of these additives are

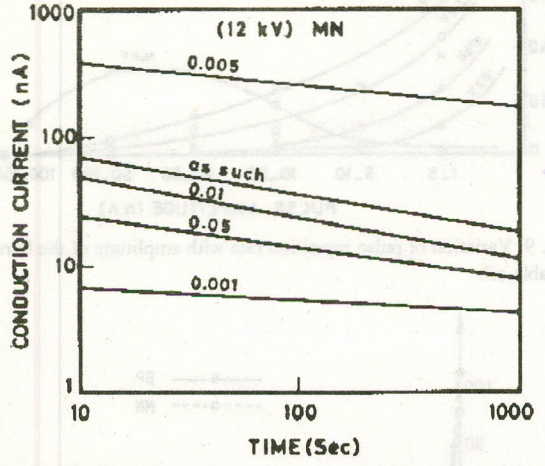

Fig. 5. Effect of additive concentration on i-t characteristics of oil samples. Values given on curves represent molar concentration.

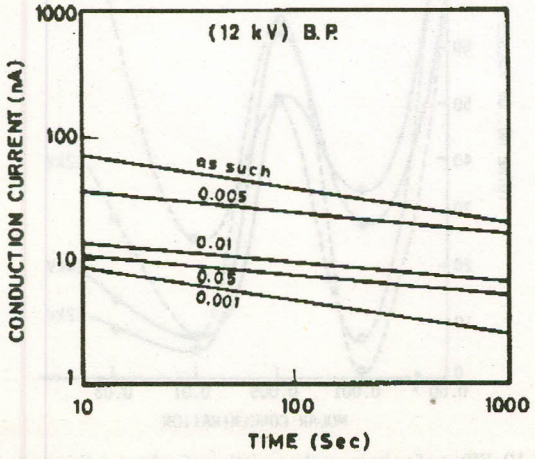

Fig. 6. Effect of additive concentration on i-t characteristics of oil samples. Values given on curves represent molar concentration.

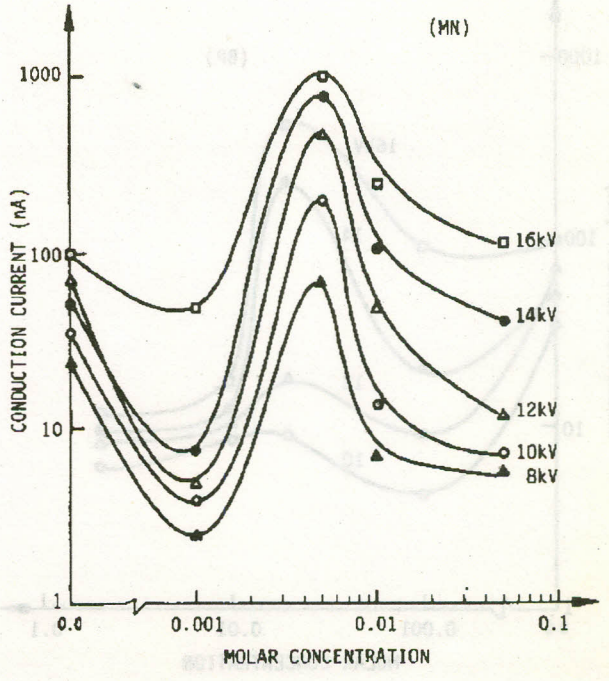

Fig. 7. Effect of voltage on the conduction current with the variation of additive (MN) concentration in cable oil.

diaromatic and possess large electron trapping crossection. However, the presence of oxygen in benzophenone molecular structure makes it comparatively more efficient electron scavenger. Therefore, its presence in oil as compared to MN is more effective in reducing and in particular the field induced component of quasi-steady conduction current.

Effect of additives on current pulses. It is well known [4,6-8] that quasi-steady conduction current is always superimposed with pulses which appear in definite shapes but their occurrence is alwasy random in nature. Their source of occurrence is not yet resolved and controversies continue, as some workers attribute them to suspended impurity particles [9,10] whereas others consider either the gas bubbles as the reason [7,8] or the initiation of partial discharge activity in oil [10]. Figure 9 displays the behaviour of pulse activity due to increasing stress level on the cathode point. The repetition rate of pulses having amplitude of 1~5 nA is the highest in all cases of voltages. However, the trend changes above 14 kV, as the pre-breakdown region approaches and most of the pulses in this region are much larger in amplitude. This phenomena is similar to partial discharge activity reported earlier.

Figure 10 displays the role of these additives on the pulse activity at two different respective voltage level. It is also interesting to report that the trend of these curves is not only similar at these two stresses but from a voltage level of 10 kV up to near breakdown. It is clear that the number of pulses increases or decreases depending on the amount of concentration of additive. The results also demonstrate that fresh oil causes a higher content of number of pulses, but the addition of 0.001M content of both additives quenches considerably the pulse activity. This is consistent with the reduction of 'i' as reported in section 3.1. This means that if there is discharge or bubble generation tendency in fresh oil then the presence of 0.001 M content of MN and BP suppresses this activity. Therefore, a further increase in the concentration of electron trapping impurities should further suppress the initiation of pulse activity. But contrary to that, with the increase in concentration to 0.005 M, not only the current amplitude increases but the level of pulse repetition rate is also enhanced. This trend of parallelism between current and burst activity continues up to an additive concentration of 0.05M, whereafter this trend

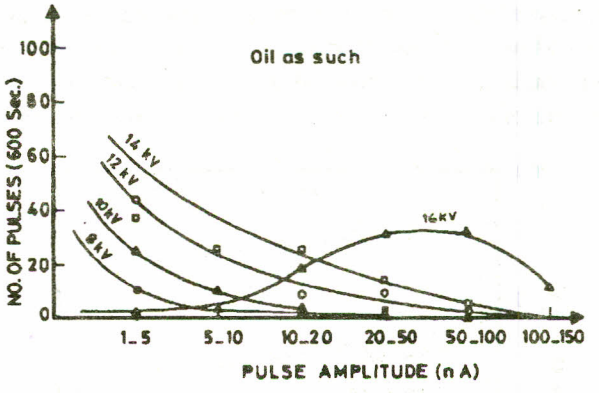

Fig. 9. Variation of pulse repetition rate with amplitude of the burst for fresh cable oil.

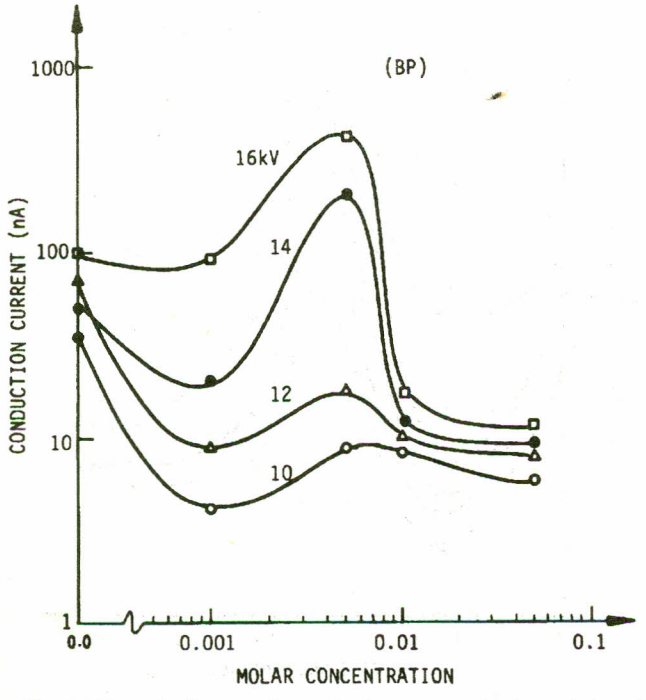

Fig. 8. Effect of voltage on the conduction current with the variation of additive (BP) concentration in cable oil.

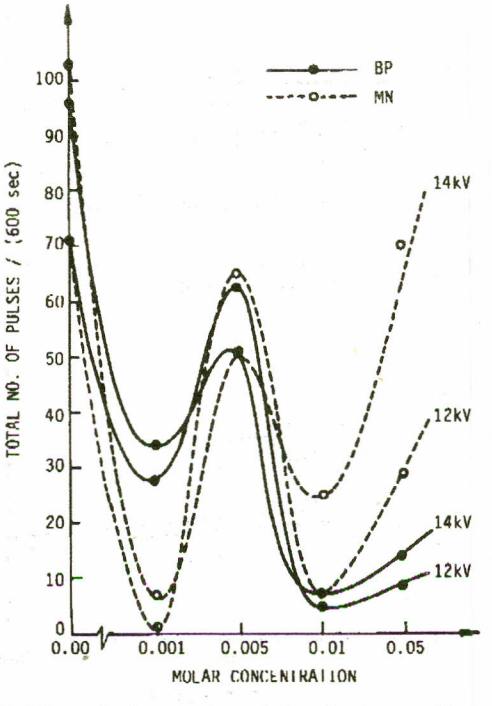

Fig. 10. Effect of voltage on the variation of pulse repetition rate due to different concentrations of additive in cable oil.

departs. This shows that in this regime of additive concentration (≤0.05M), two processes are operative simultaneously. Whereas the magnitude of quasi-steady conduction current near the cathode seems to control the initiation of pulses and hence the gas phase, the instantaneous space charge volume surrounding the cathode not only contributes by controlling the current level but also helps in suppression or atleast in retarding the initiation of the gas phase. Recently Denat *et al.* [11] have shown that the frequency of occurrence of current pulses under point as cathode in cyclohexane is directly proportional to the magnitude of conduction current flowing in the point to plane electrode gap. Present results are therefore inclined toward the process of generation of current pulses as due to vaporization of liquid films adhering to the cathode tip whenever the conduction current density at the cathode tip attains a propitious level. This hypothesis therefore suggests that the early ideas of bubble development as conjectured by Watson and Sharbaugh [12] were reasonable.

In the regime of additive concentration (≥0.05M), the conduction current level either declines with increase in concentration or becomes almost stable (Figs. 7 and 8), but on the contrary the current pulse activity gets excited again. Devins *et al.* [13] and later Beroual and Tobazeon [14] have shown under pulsed voltage and with point negative that by doping various insulants with electron trapping aromatic additive the discharge growth is not only increased but generation of secondary streamers is also facilitated. These secondary streamers appeared to grow from the primary bush structure of discharge. Increase in additive concentration resulted in more branches of this secondary steamer. But it must be noted that both groups of researchers employed higher concentrations of additives then the concentrations employed in the present experiments. Once a discharge (bubble) is initiated then the space charge trapped at its surface will reduce the cathode field but will increase it toward the anode. The columbic repulsion will facilitate its expansion, whereas increase in field at bubble's surface facing the anode (if approaches an appropriate level) can generate secondary set of streamers. Both of these processes can result in an increase of number of associated pulses. It is most likely that in the present experiments with the presence of additive concentrations below the optimum level, surface charge on the bubble is not strong enough to accelerate its growth. But as soon as level of concentration exceeds optimum, this effect becomes prominent thus leading to faster growth and generation of secondary streamers resulting in re-excitation of associated current pulse activity.

These results therefore, display the nature of conduction pulses as electrochemical, since these phenomenon cannot be explained in terms of particle charging and discharging at opposite electrodes as stipulated in literature [8,9].

Effect of additives on dielectric properties. Relative permittivity 'ε_r' and loss angle 'tanδ' are important parameters since they determine the design limitations regarding operating current and voltage levels of a power cable. For an economical design and operation, dielectric loss of paper insulation must be as low as possible. Therefore, to explore the influence of varying additive concentrations in oil and oil-paper composite, the values of ε_r and tanδ were also investigated. Table 1 summarizes these results. It is clear that with the addition of 0.05M (MN) in oil the loss angle is reduced by an order of magnitude. In case of BP with 0.01M concentration the reduction is small but with a further increase in concentration to an optimum value of 0.05M (as observed earlier both under conduction and burst current) the loss angle decreases almost by a factor of five. When kraft paper was impregnated with mineral oil its loss angle reduced from 2.19×10^{-2} to 9.41×10^{-3}. This type of reduction in tanδ is well known and is attributed to space charge-limiting effcts thay may be formed in the vicinity of solid film boundaries that are found to be characteristic of very thin-film solid dielectrics [15]. However, presence of impregnent containing 0.05M (MN) in oil-paper composite was found to increase tanδ. But contrary to that with 0.05M (BP) loss factor declined by 15% as compared to oil-paper composite prepared with undoped impregnent.

TABLE 1. EFFECT OF ADDITIVE CONCENTRATION ON THE ε_r AND tanδ OF OIL AND OIL-PAPER COMPOSITE.

Sample	ε_r	tanδ
Oil as such	2.243	0.02298
Oil + 0.05 M-(MN)	2.244	0.0022
Oil + 0.01 M-(BP)	2.256	0.02026
Oil + 0.05 M-(BP)	2.2982	0.00445
Paper without impregnation	1.7456	0.0219
Paper + Oil as such	2.3390	0.00941
Paper + Oil with 0.05 M-(MN)	2.468	0.011
Paper + Oil with 0.01 M-(BP)	2.44	0.01239
Paper + Oil with 0.05 M-(BP)	2.277	0.008

Table 2 depicts some representative results showing the effect of these additives on the power frequency breakdown voltage of impregnated paper. It is clear that at optimum concentration level of 0.05 M the breakdown strength is increased by 15% with MN and around 24% with BP.

A more comprehensive study of oil and oil-paper composite doped with a larger range of varying concentrations of additives while considering the effects of temperature, on the parameters reported above as well as the lightning and switching impulse breakdown is in progress and will be reported later.

TABLE 2. EFFECT OF ADDITIVES ON THE 60 HZ BREAKDOWN VOLTAGE OF IMPREGNATED PAPER.

Samples	Range (KV)	Average (KV)	%age increase
Paper without impregnation	2.05-2.6	2.55	–
Paper + Oil as such	7.25-7.8	7.42	00
Paper + Oil with 0.05 M-(MN)	8.00-8.75	8.53	15
Paper + Oil with 0.05 M-(BP)	9.00-9.5	9.2	24

Conclusions

The results presented here are part of a continuing research. However, the following conclusions can be drawn tentatively.

(i). Presence of trace amount of aromatic additives in cable oil decreases the conduction current and burst current levels but these are confined to an optimum molar concentration.

(ii). Conduction current pulses are a consequence of electrochemical reactions under the action of high field stress and not due to interelectrode migration of particles.

(iii). Addition of 0.05M Benzophenon in impregnating oil improves more than 20% the power frequency breakdown voltage and reduces by 15% the loss angle of oil paper composite.

Acknowledgement. We are thankful to SCECO (Central) Saudi Arabia for providing cable oil samples and to Hitachi Cable Co. Ltd., Japan for providing us with virgin samples of kraft paper used in 132 kV underground cable installed in Riyadh region.

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