Research Article

Influence of load-shedding and night on SiR insulator environmental aging under AC test voltages

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Received: 1 November 2020 / Accepted: 8 January 2021

Abstract
Insulators play a critical role in healthy transmission under the influence of operational stresses (OSs). OSs include environmental stresses (ultraviolet-radiations, seasonal heat and humidity variations, and pollution (inert and active), etc.) and electrical stresses (electric field distribution, corona, etc.). OSs can deteriorate insulators, jeopardizing the healthy transmission. In this experimental study, four silicon rubber (SiR) insulators with different concentrations of micro and nano-silica fillers are tested in a specially designed and fabricated compact environmental chamber for 1920 h under OSs, un-scheduled load shedding, and night factors for more realistic field insulators deterioration characteristics. Insulators' potential distribution, electrical field distribution, hydrophobicity, and leakage current characteristics are considered. Experimental results reveal OSs affected insulators' leakage current profile due to hydrophobicity loss and electric field distribution variations. Moreover, SiR insulators under OSs regained insulation characteristics due to heavier inner molecule replacement to the dissipated and degraded outer lower weight insulating molecules. This property provides a reusability opportunity for SiR insulators in power system networks, unlike traditional insulators.

Keywords SiR insulators · Operational stresses · Overhead transmission line · Leakage current · Hydrophobicity

1 Introduction

Electrical energy has high growing demand, and its power plants are far located from human populations [1]. The most economical way to transfer electrical energy is through overhead transmission lines (OTL). In OTL, the electrical energy is transformed at lower current values and extra-high voltage (HV) levels to reduce the copper losses (I2R) [2]. HV line insulators play an important role by electrically isolating the three phases and ground from one another while, providing mechanical support to current carrying conductors [3]. However, insulators on HV OTL are exposed to multiple stresses, detail is provided in [4]. These operational stresses (OSs) include environmental stresses (ultraviolet radiations, sunlight, heat, humidity, pollution, etc.) and electrical stresses (electric field distribution, corona, etc.). OSs can compromise the dielectric characteristics of insulators over time, hence compromising their useful life. Moreover, other than OSs, insulators' performance and the probability of flashover also depend on some other factors such as material, shape, degradation characteristics, and type of pollution [5]. Loss in dielectric properties of insulators due to OSs in OTL can cause large-scale power outages [6]. Hence, the literature is focused on OTL insulators' performance in the presence of OSs.

OSs varies from location to location. Depending upon the location of insulators, multiple factors may be acting together to cause insulators' deterioration, and these were the cause of 2nd and 3rd generation polymer insulators' failure [7–10]. Early insulators suffered from weather and

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SN Applied Sciences (2021) 3:190 | https://doi.org/10.1007/s42452-021-04193-4

Published online: 24 January 2021

degraded by UV radiations. And research diverted to other materials as insulators [11]. The industry witnessed the shift to porcelain due to its environmental stress inertness [7, 12]. Which later proved other factors' role in its insulation degradation [11]. However, polymer insulator showed superior performance in the presence of pollutants over ceramic and fiberglass insulators [13]. And China shifted to polymeric insulators over these advantages [14].

A subtype of polymer insulators; silicon rubber (SiR) are widely used insulators due to their excellent dielectric properties; resisting freely movement of internal electric charges (resistivity > 1012 Ω), blocking current conduction under the influence of an electric field, lightweight, hydrophobic nature, high contact angle of water droplets, transfer of hydrophobicity, and prone to pollution; hence replacing ceramics in HV OTLs.[3, 8, 15–21]. Details are available at [3, 22].

SiR organic in nature, have weaker bonds and when exposed to OSs loses its desired properties with an impact to its lifetime [3]. OSs can deteriorate the chemical, physical, and electrical properties of SiR. For instance, alterations in the composition, surface morphology, and reduces hydrophobicity. These changes occur typically at the top few monolayers of polymeric insulators [12]. Therefore, the life expectancy of polymeric insulators in a laboratory simulating actual field conditions is an important area of research [23]. Insulators' deterioration under OSs is simulated in an accelerated aging system to predict the changes that might occur and the long-term performance of insulators in service suffers. Data obtained from such tests are used for insulators life estimation [8].

1.1 SiR dielectric loss causes

Pollution, strongly correlated with its vicinal condition, sternly affects the performance of outdoor insulators and in favourable conditions leads to flashover [1, 24, 25]. Pollutants deposition on the insulator surface, causes the change in potential and electrical field distribution across the insulator, soluble pollutants with water forms a conductive path causing flashover of insulator and increase of power dissipation of insulator [26].

Insulator characteristics deteriorate in the presence of sunlight and UV radiation. These radiations have impacts like crazing, chalking, colour-changing, and brittle fracture due to the breaking of long polymeric chains [27, 28]. Ultraviolet radiation penetrates to the molecular level, destroying composite material [5]. High energy ultraviolet radiations can break the long chains to short, resulting in hydrophobicity loss [15].

Insulator surface characteristics erode due to corona and arcing [15]. Corona varying with air-density and humidity is accompanied by UV light, heat, and gaseous by-products (ozone, NO_2) and corona discharges leave severe electrical strains and chemical degradation of insulators. Prolong exposure leaves polymer unusable [29]. Heat and light produce surface cracking and erosion [12].

Polymeric materials, inert to bio-contamination but micro-organisms colonizing on insulator surface use pollutants from the environment to gain nutrition compromising surface properties of an insulator and causes pigments production, which diffuses into the matrix of a polymeric material leaving stains and, in some cases, become the sources of odour. Fungal hyphae penetrate and cause cracks and pores, reducing mechanical stability and a way for water to enter the material which increases the electrical conductivity of an insulating material [17, 30].

Electric field influences the size and shape of water droplets on the surface of SiR, while electric field distribution on insulator varies due to water droplets, which may lead to corona discharge and even flashover [15].

1.2 Dielectric loss impact on SiR

Hydrophobicity property resists the formation of a continuous layer on SiR surface in wetting conditions, this property is highly required in case of moderate to heavy pollution [3, 31, 32]. Hydrophobicity reduces the formation of water layers on the surface of the insulator which reduces leakage current and development of dry bands [3]. However, in harsh conditions, SiR may lose its hydrophobicity properties [3]. Hydrophobicity loss increases leakage current, deterioration effects, and chances of flashover [33, 34]. Leakage current is an important tool to investigate insulators' electrical surface activity [1].

The aim of this experimental study is to investigate the aging phenomena of SiR insulator in close to realistic conditions. Since SiR insulators with faults in OTL has no defect in the laboratory test, it means a difference between laboratory and actual OTL aging [35]. Moreover, developing countries like Pakistan suffer from energy shortages [36] so load-shedding is inevitable and has an impact on the aging of SiR since electrical stresses are removed. In the case of night, insulators are no longer under the influence of direct sunlight and UV radiations, etc. In this paper, the experiment is carried out in a specially closed and compact chamber to study the behaviour of four different types of silicon insulators (Silicon Nano Composite (SNC)-2.5-SiO_2, SNC-5-SiO_2, neat silicon rubber, and Silicon Micro Nano Composite (SMNC)-10μ2n-SiO_2, with silica fillers) under OSs; with two new effects; unscheduled load-shedding and night, which any insulator in-service experiences and are not considered before.

Table 1 Fillers scale

Filler	Size
Micro	Diameter > 100 nm
Nano	Diameter < 100 nm

2 Materials and filler

2.1 Fillers

Fillers are additives, providing additional characteristics to materials. Fillers have different sizes ranging from microscales and nanoscales, shown in Table 1. As per the literature, fillers significantly improved the performance of polymers [3].

Microscales insulators improve thermal characteristics and nanoscales advance polymer life. More detail of fillers and their effect on base materials are provided in [3].

2.2 Materials

Four different compositions of silicon polymeric insulators are investigated under OSs. In this experimental setup, silica fillers are used to provide silicon rubber insulation characteristics like anti-erosion, anti-tracking thermal conductivity, and mechanical strength to composite materials [3]. The size and purity level of each sample is kept constant, which is discussed in Table 2.

3 Experimental setup

To study the effect of OSs, which insulator bears in operation, a closed and compact environmental chamber (WAMM) was designed and fabricated to minimize the external effect. Chamber with four feet high, four feet long, and three feet in width is equipped with sensitive sensors to measure especially humidity and temperature variations. Chamber has the equipment to vary temperature using hot plates and blowers, humidity using humidity generator/ water bowl, ultraviolet radiations using the UV lamps, etc. these all are controlled using feedback of sensors to maintain the required conditions inside of the chamber with the tolerance of 0.5 bands.

Outside of the chamber, a transformer of 230/2500 V serves as a source of electrical stress on testing insulators. An LCD is installed on the right corner of WAMM for real-time chamber variables (temperature and humidity mainly). The display is updated after every 5 s. Chamber outlook is shown in Fig. 1.

3.1 Modification in testing system

Polymeric insulators are tested with two extra specifications, night effect and unscheduled- load shedding effect to consider the developing countries scenarios [36] as due to load shedding, insulators are not all the time under the influence of electrical stress but only under the

Table 2 Materials specifications

Insulator	Filler and concentration	Width of sample (mm)	Diameter of sample (mm)	Purity (%)
SNC-2.5-SiO_2	2.5% Nano Silica	33	81	99
SNC-5-SiO_2	5% Nano Silica	33	81	99
Silicon rubber	Neat silicon Rubber	33	81	99
SMNC-10µ2n-SiO_2	10% micro, 2% Nano silica	33	81	99

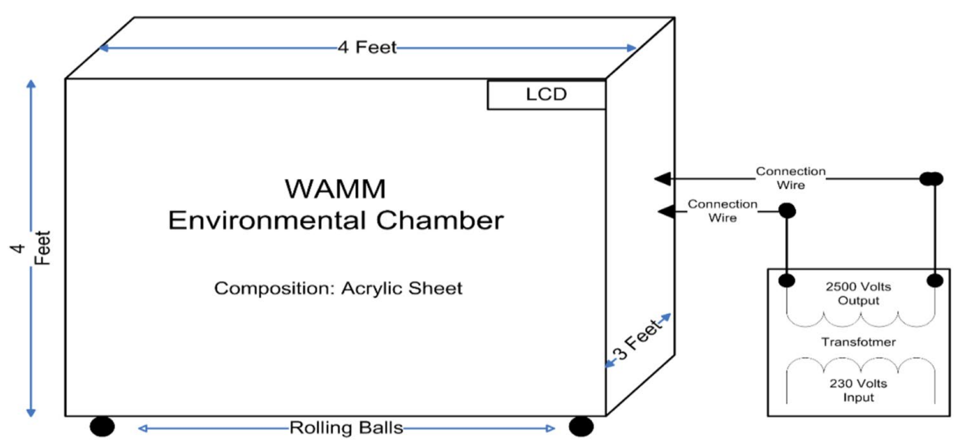

Fig. 1 WAMM environmental chamber outlook

environmental stress, and at night, UV radiations intensity drops to zero. So, these two additional effects are considered in testing and these served as the base of modified environmental aging results.

Since field insulators are not all day subjected to Sun's radiations. So, in night effect, UV radiation counterpart UV lamps were turned off for a consecutive couple of hours at the end of every week. On the other hand, voltage stress over insulators was removed for some hours at irregular time intervals to create the scenario of unscheduled load shedding (it can be considered as a fault case, no electrical operation of OTLs).

3.2 Operation of WAMM

WAMM was operated for 1920 summer season hours. The temperature was maintained to 47 °C with a tolerance of 0.5 bands. WAMM Specifications are discussed in Table 3. Inert pollution; dust was used on all four types of silicon polymeric insulators with 0.5 mm thickness layer. While, active pollution; fly ash and metal particles were maintained to uniform light- pollution severity level over the surface of the insulator to maximize the impact of unscheduled load shedding and night effect.

4 Results and discussion

4.1 Potential distribution

Potential distribution along the surface of insulators has a significant impact on the performance and useful life of insulators. Therefore, it is important to know the potential distribution along the insulation surfaces used for testing.

Table 3 WAMM environmental chamber specifications

WAMM chamber	Specifications
Dimensions	4×4×3 feet
Chamber walls	Acrylic sheets (6 mm width)
Chamber top	Acrylic sheet (8 mm width)
Movability	Four—3-inch diameter, rolling balls
Transformer connection	High voltage inlets
Solar counterpart	Two-UV lamps
Heating/temperature	Hot plate and blower
Humidity	Humidity bowl/humidity generator
Fog	Fog bowl, clean and light salty
Real time output	LCD on top corner (humidity and temperature parameters)
Protection	UV blocking covering on walls
Pollution	Inert and active (light)
Additional modes	Night effect and load shedding effect

The potential distribution along the insulation in both dry and wet conditions was found to be uniform. Light pollution was applied to all samples and it was observed that light pollution has no or little effect on potential distribution. All simulations were carried out in Comsol Multiphysics. The simulated effect of uniform light pollution on insulators inside WAMM is given in Fig. 2.

4.2 Electric field distribution

Electric field distribution along the insulator surface is another important indicator of the surface condition of the insulation. The insulation used for testing were exposed to uniform pollution and electric field distributions were calculated in Comsol Multiphysics. Electric field along the surface of insulator was affected in case of active pollution. In dry cases, electric field distribution was lower compared to wet conditions, maintaining the light-pollution severity level and its electrical conduction was increased affecting its hydrophobicity and leakage current characteristics. The simulated effect of uniform light pollution on insulators inside WAMM is given in Fig. 3.

4.3 Hydrophobicity

Hydrophobicity improves the pollution performance [3] Hydrophobicity pictures SiR degradation as the result of OSs in the form of leakage current increment, so it's the effect on silicon polymeric insulators before the operation and after 1920 h of operations are discussed as per Swedish Transmission Research Institute (STRI) hydrophobicity classification. Figure 4a shows HC 1, hydrophobicity level but after 1920 h modified environmental investigation, Fig. 4b. reveals different hydrophobicity outcomes, SNC-2.5-SiO_2 and SNC-5-SiO_2 degraded to

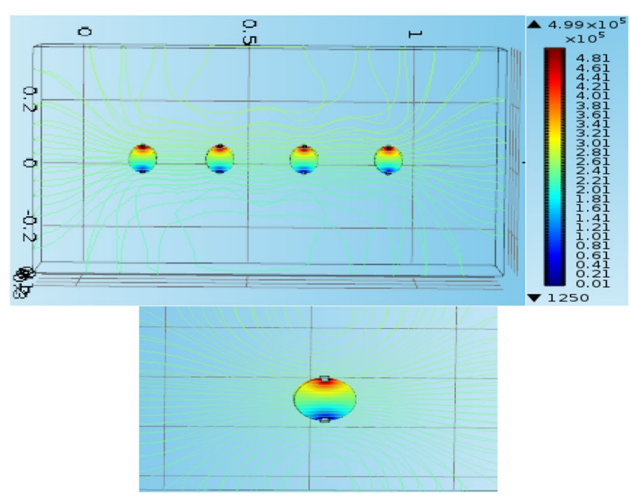

Fig. 2 Effect of pollution on potential distribution

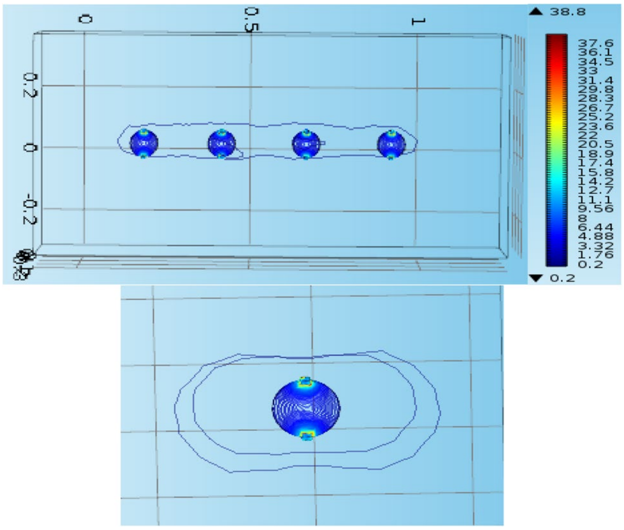

Fig. 3 Effect of pollution on electric field distribution

HC2 and in between HC2 and HC3 respectively. While neat silicon rubber reduced to the level in between HC2 and HC3 but higher compared to SNC-5-SiO_2. However, SMNC-10μ2n-SiO_2 reduced to HC3 level.

4.4 Leakage current

Monitoring of leakage current enables the evaluation of surface degradation (tracking and erosion) of an insulator, directly related to insulator surface wettability [31]. The allowable limit to leakage current is based on their reliability rather than safety and it varies from country to country [1].

However, the maximum allowable leakage current for OTL is 100 mA depending upon the type of insulator, voltage rating, and OTL losses [1]. SiR under operational stresses for 1920 h yields insulation characteristics, which are measured by measuring insulators leakage current and are shown in Table 4 below.

4.5 Result discussion

The composition of SiR insulator includes three parts; high-molecular-weight substances, low molecular substances, and fillers [16]. Lower weight molecules exist on the surface while heavy molecules inside the insulator. Polymeric insulators' strength is due to their entanglement of chains and higher molecular weights. Due to high OSs, lower weight molecules depart from the insulator with time, and silicon insulator losses its insulation property. Afterward, heavy molecules breakdown occurs into lower weight molecules to replace previous molecules on the

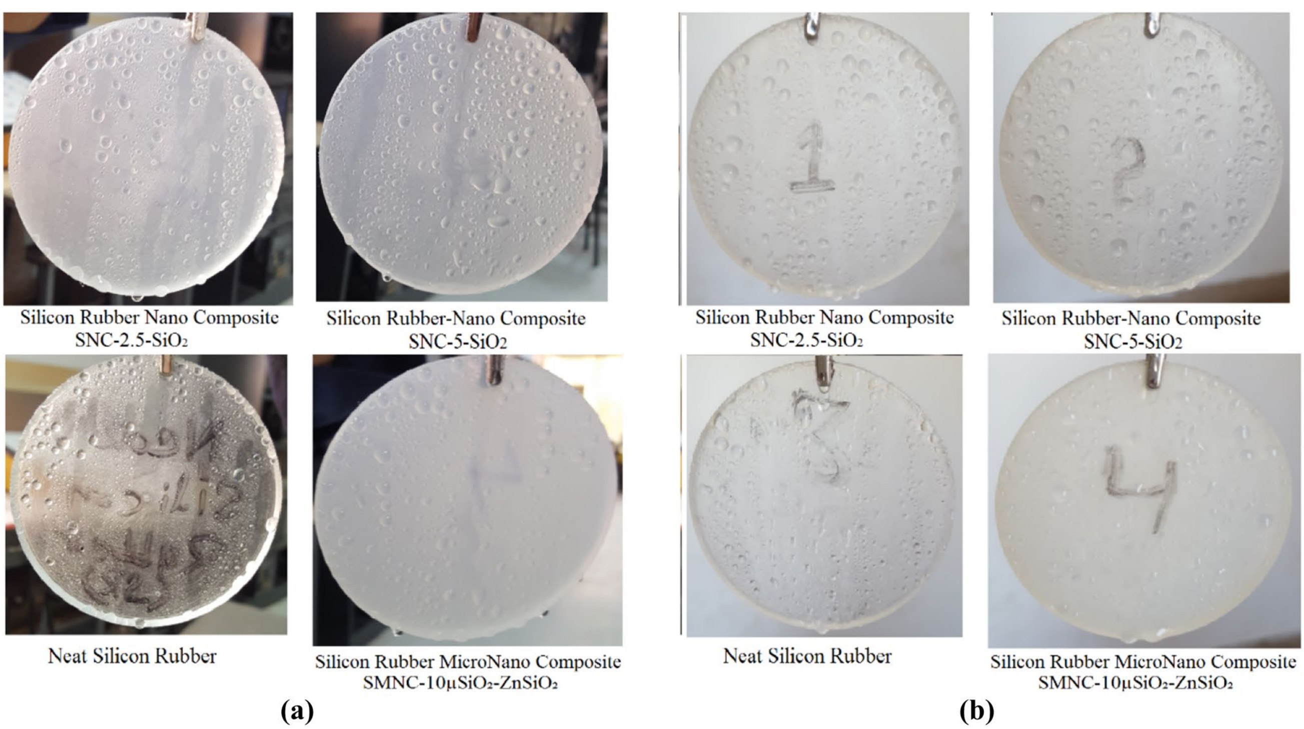

Fig. 4 **a** Pre-operation samples hydrophobicity. **b** After 1920 h, samples hydrophobicity

Table 4 Insulation characteristics of SiR insulator

Insulator composition	Pre-operation leakage current (μA)	Current after 480 h (μA)	Current after 840 h (μA)	Current after 1200 h (μA)	Current after 1560 h (μA)	Current after 1920 h (μA)
SNC-2.5-SiO_2	0.8	0.9	0.6	0.8	0.6	0.5
SNC-5-SiO_2	0.8	0.9	0.6	0.8	0.7	0.8
Silicon rubber	0.7	1.1	0.6	1.0	0.8	0.8
SMNC-10μ2n-SiO_2	0.5	1.4	0.8	1.2	1.1	0.9

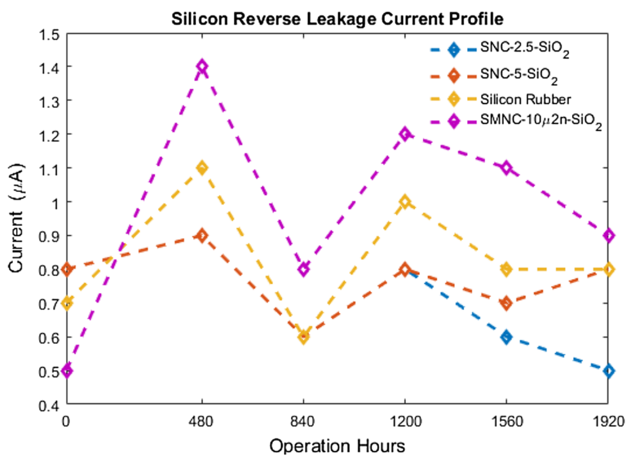

Fig.5 SiR leakage current profile

surface, hence the silicon polymeric insulator regains its insulation properties while losing some molecular weight as shown in Fig. 5. This results in the reduction of hydrophobicity of SiR insulators, detail is provided in [23].

Electrical and chemical properties of polymeric insulators surface are critical for its reliable insulator performance. 1920 h exposure to OSs, un-scheduled load shedding, and night factors caused several changes in SiR composition resulting in the degradation of hydrophobicity.

However, Leakage current same pattern was observed in SiR type insulators in [31]. However, if compared with 2000 h testing results of studies in [31, 37, 38], SiR sample insulators offered high resistance to leakage current.

5 SiR samples comparison

Comparative results reveal the leakage current profile of different SiR insulator samples. Due to the difference in polymeric insulators' molecular composition hence, the difference in molecular weight for polymeric insulators, their leakage current is different being subjected to the same testing conditions.

All four silicon rubber insulators showed insulation characteristics recovering property after the loss of insulation characteristics over the 1920 h under OSs, un-scheduled load shedding, and night factor. Individual insulation characteristics of each silicon insulators are shown in Fig. 6a–d.

Provided all stresses, each insulator depicted reverse leakage current characteristics over the operation time. SNC-2.5-SiO_2 insulation characteristics/molecular degradation and recovering properties compared to rest are comparatively higher. While SMNC-10μ2n-SiO_2 characteristics as polymer insulators compared to rest is at least.

6 Conclusion

To ensure the safe and sound power flow in power system networks, insulator aging behavior and characteristics under multiple factors role is a hot topic of research. Multiple factors include operational stresses such as environmental (UV radiations, humidity, temperature, fog, pollution, etc.) and electrical stresses (electrical field distribution, potential field distribution, etc.), load shedding, and at night effect. Silicon rubber polymeric insulator (SiR) offers a way out by regaining its insulation strength under multiple stresses after losing it first, prone to pollution, lightweight, and availability in nature, etc. The experiment was carried out in a specially designed environmental chamber for 1920 consecutive hours under all factors and their stress. Moreover, the silicon nanocomposite insulator (SNC-2.5-SiO_2) provides the best alternative in terms of performance (leakage current and hydrophobicity) compared with the rest of SiR insulator samples with suitability in outdoor high voltage insulator application, capable of completely replacing ceramic and fiberglass insulators.

7 Future research work

Future works include continuing the preliminary testing as per IEEE Standards and measuring its hydrophobicity, leakage current, potential distribution, electric field distribution and using techniques like FTIR Analysis, SEM Analysis, and Energy Dispersive Spectroscopy X-Ray (EDX) for silicon polymeric composite insulators complete aging characteristics.

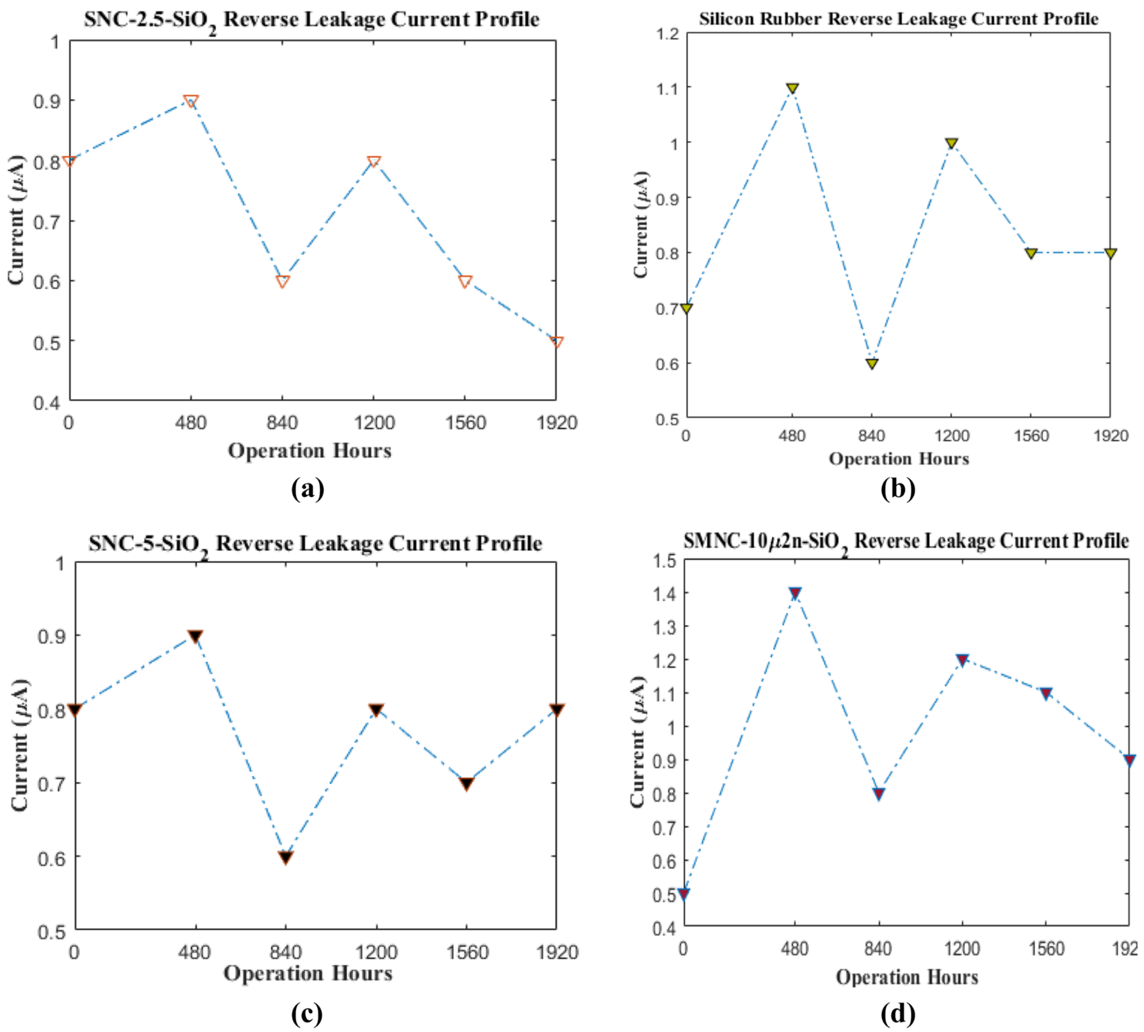

Fig. 6 **a** SNC-2.5-SiO_2 leakage current. **b** SNC-5-SiO_2 leakage current. **c** Neat Silicon Rubber leakage current. **d** SMNC-10µ2n-SiO_2 leakage current

Acknowledgement We would like to acknowledge the extraordinary support of Engr. Abid, Engr. Musa and Engr. Moshin.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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