International Journal of Applied Power Engineering (IJAPE)
Vol. 10, No. 1, March 2021, pp. 41~47
ISSN: 2252-8792, DOI: 10.11591/ijape.v10.i1.pp41-47

Investigation of 22 kV silane cure TR-EPR cable

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Article Info

Article history:

Received Sep 22, 2019
Revised Feb 19, 2020
Accepted Sep 19, 2020

Keywords:

Cross-linking
Partial discharge
Silane cure
TR-EPR
XLPE

ABSTRACT

EPR-insulated cables for distribution power network are not commonly used in Australia. This is due to the higher DDF of common EPR cables when compared with XLPE that contributes to the power loss and economics in transmitting electricity. This led to the development of EPR called TR-EPR with significantly lower DDF and uses silane curing process to address concerns about cost-effectiveness. The thermal behavior of low DDF silane cure TR-EPR is investigated for 30 months of exposure to the maximum operating temperature of material. The physical changes in the samples throughout the long-term aging are examined to create an opportunity to model the expected life cycle of TR-EPR cable under thermal stress. The cross-linking characteristics of TR-EPR cable are also examined by ambient curing that simulates the storage condition for unused cable and by cable heating process that simulates the condition when the cable is energized. The results are tabulated for a better understanding of the time for the material to cross-link at various conditions. The improved partial discharge values after cross-linking are also presented.

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1. INTRODUCTION

POLYMERIC insulated underground cables for medium voltage (MV) distribution network are first introduced in early 1940s utilizing Polyethylene (PE) insulation [1, 2]. PE underground cables are susceptible to treeing phenomena which is then replaced by cross-linked Polyethylene (XLPE) in 1960. It was only in 1980 that Ethylene propylene rubber (EPR) cables are commercialized and introduced to the power system due to its low permittivity, high dielectric strength, good thermal resistivity, and resistance to water treeing [3]. EPR and XLPE are the most commonly used solid dielectric polymeric insulated material for MV distribution network nowadays.

There are several studies on EPR cables conducted since the introduction of EPR to the power industry. Brown [4] studied XLPE and EPR from 1981 to 1991 and found that EPR has a better electrical characteristic over XLPE cable at temperature above 90°C as XLPE produces drop in electric breakdown above its crystalline melting point. Montanari [5] performed various studies on space charge of dielectric materials and found that EPR cable has large values of endurance coefficients associated with high dielectric strength that give rise to lifelines even at relatively high electrical and thermal stresses. Arhart [6] expressed that EPR has excellent electrical properties which is comparable to XLPE. However, these studies are not sufficient for power network operators in Australia to consider EPR cable over XLPE cable for their underground cabling distribution lines. One possible reason could be due to the high dielectric dissipation factor (DDF) and permittivity of most common EPR cables that contribute to network power loss. Another possible reason is the higher cost of EPR insulation compared to XLPE [7]. This led to the development of the state-of-the-art EPR insulation called tree-retardant EPR (TR-EPR) which offers significantly improved dielectric properties especially the DDF at reasonable economics through silane method of curing.

DDF refers to the ratio of energy dissipated to the insulation and energy stored in each cycle when AC voltage is applied [8]. While XLPE has a low DDF than standard EPR, TR-EPR has lower DDF compared to XLPE as listed in Table 1 [9]. Low DDF material has a low dielectric loss. However, the dielectric loss of material is usually less significant in MV level where all power distribution networks operate. These are the areas where EPR cable can be utilized and since the dielectric loss angle of EPR can be lowered due to modern compounding technology, the loss due to insulating material is almost negligible when life cycle analysis is considered as presented in (1):

$$W_d = \omega C\, U_o^2 \tan \delta \qquad (1)$$

where W_d is the dielectric loss (W/m), ω is the angular frequency, C is the capacitance per unit length (F/m), U_0 is the voltage to earth (V), and tan δ is the dielectric loss angle of material or DDF [9]. For instances where DDF is really taken into account, TR-EPR serves as great consideration for the insulation material as alternative for EPR over XLPE. In this paper, the long-term aging and partial discharge behavior of 22 kV silane ambient cured TR-EPR are investigated. This study aims to introduce this type of insulating material for use in underground distribution MV networks in Australia.

Table 1: DDF of XLPE, EPR and TR-EPR (measured)

Dielectric material	DDF
XL PE	0.004
EPR	0.02
TR-EPR	0.0002

2. SILANE CURE TR-EPR

EPR like XLPE can be cross-linked by peroxide, silane, or irradiation method. Peroxide cross-linking method is commonly used in MV and HV cable manufacturing whereas silane and irradiation methods are used for LV cable production. The compound used in peroxide method is clean and cross-linking takes place in molten state leading to more homogeneous cross-linked reaction and therefore suitable for cable above 30 kV. However, this method has a high capital investment compared to silane method [10]. Silane method has a low start-up investment and can be processed by using the conventional PE extrusion machine. The catalyst masterbatch is added and mixed with pellet into the hopper mixing station prior to entering the extrusion screw feeding zone. Unlike peroxide where cross-linking takes place within the chamber after extrusion, silane ambient cure can take days before the molecules start to bond. Cross-linking can be achieved by simply storing the extruded cable at ambient temperature. The cost of silane ambient cure material is slightly higher compared with peroxide curing, but this cost is outweighed by the minimum material scrap cost. Despite prolonged time in the cross-linking via silane method, the properties of the material (TR-EPR in this case) exhibit satisfactory values as shown in the results of the experiment. This aspect of silane method offers advantage in the economics of the insulation when cost is greatly considered.

3. EXPERIMENTAL STUDY

3.1. TR-EPR cable sample

Sample is 22 kV cable with cross-sectional area of 120 mm^2. The cable construction is presented in Figure 1. Conductor is class 6 flexible plain annealed copper that consists of 1672 wires of 0.3 mm in diameter. Conductor is wrapped with 0.2 mm thick nylon semi-conductive tape with 15% overlap. The polymeric semi-conductive conductor screen, TR-EPR insulation and polymeric insulation screen are extruded simultaneously using the 3-layered single extrusion head. This method of extruding MV cable is the most widely used in cable manufacturing to avoid voids and contaminants between insulation and semi-conductive screen that could lead to partial discharge failure during routine and qualification tests. The polymeric materials including the TR-EPR insulation are processed through silane dry cure method with the addition of 5% catalyst master batch. Prior measurements conducted separately show that the TR-EPR insulation has a breakdown voltage rating of 50 kV/mm.

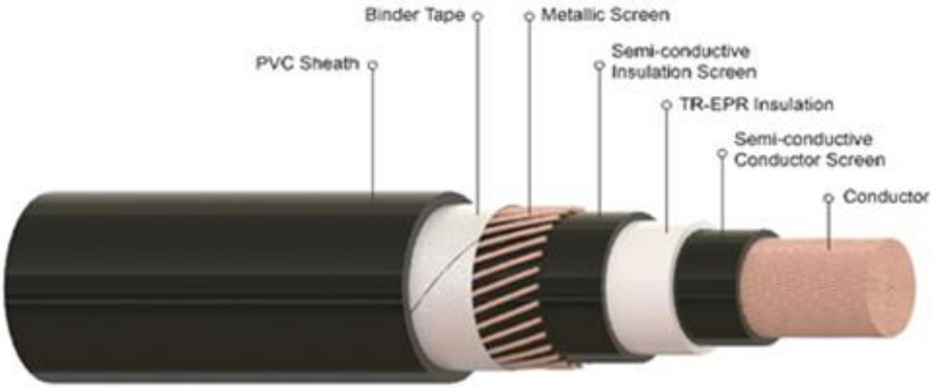

Figure 1. Construction of 22 kV 1C120 mm^2 TR-EPR cable

3.2. Ambient cure cross-linking process

This paper aims to determine the time for the TR-EPR material to reach its cross-linking state through Hot set test. Cable samples are exposed to ambient temperature in the range of 0ºC to 15ºC for several days until the material reach its cross-linked state. This is during winter time in Victoria and therefore the longest period for the material to cross-link as the rate of cross-linking is a function of time and heat. Strips of 10 mm of insulation are taken from the sample. The strips are then polished by grinding the surface of insulation to eliminate the effect of surface irregularities that could result to breaking of material during Hot set test. Hot set test determines the ultimate cross-linking stage of thermoset material [11]. The grounded specimens are conditioned at room temperature for 16 hours prior to carrying-out the Hot set test. The size of dumbbells cut from the sample is presented in Figure 2. After conditioning, specimens are placed inside the oven with mechanical load equivalent to 20 N/cm^2 suspended at the bottom of the dumbbell specimen. Test deemed to be successful when the specimen could withstand the mechanical load for 900 minutes without breaking and the value of elongation and the residual length from the initial length is less than 175% and 15% respectively.

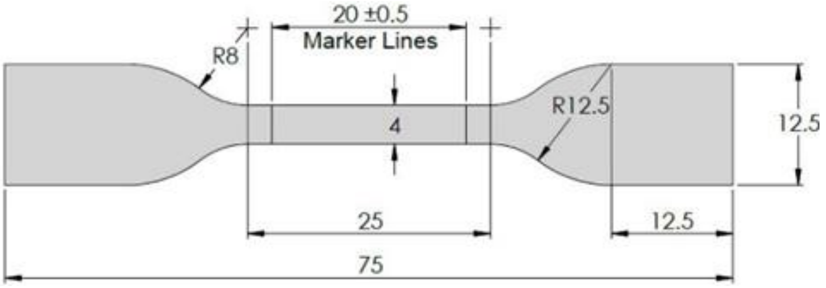

Figure 2. Dumbbell size for testing the physical property of material

3.3. Cable heating

Three 10-meters length of cable are placed onto the cable tray and looped onto the current generator. The two ends of cable are terminated using crimped copper lug. Two lugs are connected using a bolt creating a short circuit loop for the current to rise. Thermocouples are attached to the conductor as seen in Figures 3 and 4 to monitor the temperature of conductor. Load current is tuned until the conductors reached the temperature of 60ºC and until the insulation is cross-linked. Strips of insulation are taken in every 24th hour of heating interval. Preparation of specimens for testing is done based on the procedure stated in section 3.2. Partial discharge (PD) tests before and after the heating are carried-out to compare the PD values between initial and after heating.

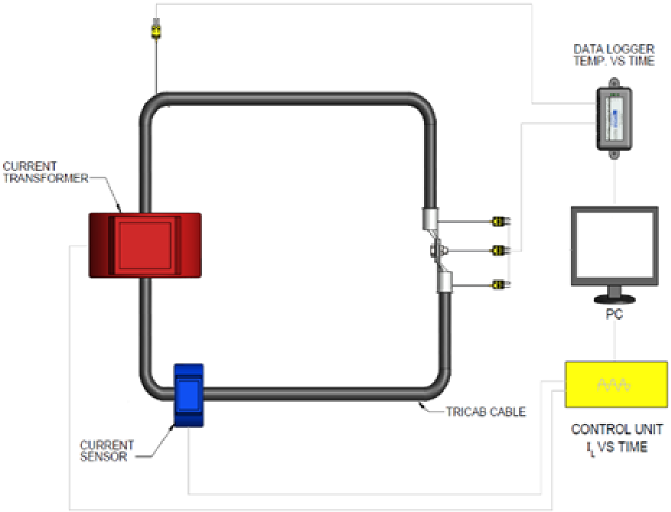

Figure 3. Diagram of cable heating process

Figure 4. Cables are subjected to 60°C heating

3.4. Long-term thermal aging

Fifty-five dumbbell insulation specimens are cut from the cable sample. The specimens are marked from S1, S2, S3… to S55 and placed inside the thermal oven and continuously aged for 30 months at 90ºC. This test aims to simulate the effect of elevated temperature to the physical property of material when the cable operates continuously at a maximum temperature permissible by the property of material. Five specimens are removed from the thermal oven every 12 weeks and conditioned at room temperature to stabilize the material and eliminate the effect of heat prior to carrying-out the tensile strength and elongation after the material breaks. After conditioning for 24 hours, each specimen is placed onto the jaw of tensiometer as shown in Figure 5. Pulling tension is applied to the specimen until it breaks. An electronic controlled tensiometer that has the capability of recording the applied peak force is used.

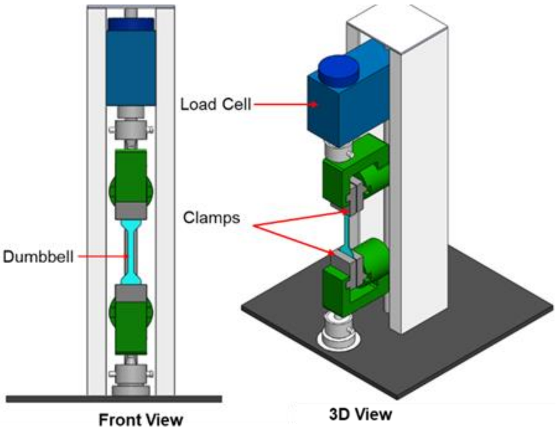

Figure 5. Diagram of tensile strength and elongation after break test

4. RESULTS AND DISCUSSIONS

4.1. Cross-linking

The values presented in Table 2 taken every 96 hours interval show the evolution of the new material structure from thermoplastic to thermoset stage. It was observed that the molecules started to change its physical and chemical properties to form a new cross-link structure 24 hours after the extrusion process. The ultimate cross-linking is achieved after 576 hours. This is the value above the requirements presented in the IEC 60502:2018 standard [12].

Table 2. Cross-linking development of TR-EPR at ambient temperature

Number of hours exposed at ambient condition	Hot set test_time after brean (seconds)
24	28
96	35
192	88
288	335
384	590
480	744
576	900 (no break)

Heat is generated when cable is energized, and this phenomenon is called conductor loss [13] and can be presented in (2):

$$\boldsymbol{P_c = I^2 R} \tag{2}$$

where P_c is the conductor losses (in W), I is the current flowing to the conductor (in A), and R is the DC resistance of conductor (in ohm/km).

The amount of heat as a result of the load current being transmitted to the cable is simulated through cable heating process as described in Section 3.3. The ultimate cross-linking of insulation is achieved after 120 hours of the cable being exposed at 60ºC as presented in Table 3. The purpose of this experimental approach is to determine the time for the cable to reach its cross-linking stage when there is not enough time for insulation to cross-link when stored at ambient temperature. Partial discharge tests are also conducted before and after the heating of cable sample. The results are presented in Figure 6. It was observed that the PD value of cable improves when the insulation achieves its cross-linking state which is an important consideration on the side of the manufacturer.

Table 3.Cross-linking development of TR-EPR at 60ºC heating

Number of house exposed at 60ºC	Hot set test_time after break (seconds)
24	650
48	722
72	780
96	845
120	900 (no break)

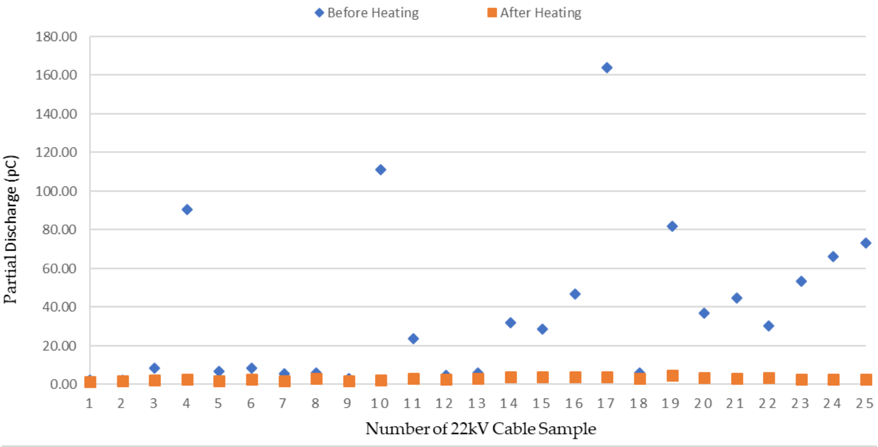

Figure 6. Partial discharge graph of 22 kV TR-EPR cable before and after heating

4.2. Long-term aging

Long-term experimental approach of the thermal endurance of insulation at maximum operating temperature is carried-out on 22 kV cable. Samples of TR-EPR insulation are subjected to 21912 hours or 30 months of continuous exposure inside the thermal oven at 90ºC. The tensile strength and elongation after break of material are measured every 3 months interval as presented in Tables 4 and 5. There is a reduction to the physical property of material after 2208 hours of exposure at 90ºC and become stable on the next 21912 hours as presented in Figures 7 and 8. The changes to the physical property of insulation from the initial stage up to the 3rd month of exposure to the oven are due to the initial effect of thermo-stress to the material. It also shows that there is negligible degradation to the physical property of insulation from exposure to heat up to the 30th month of endurance test. Despite the delayed stabilization, the physical properties of the TR-EPR are still above the standard values prior and even after the ageing.

Table 4. Measured tensile strength of 22kV TR-EPR cable from long term endurance test

Time	Date			Tensile strength (MPa)			Median
				Sample			
		1	2	3	4	5	
Initial	5 October 2016	13.1	13.2	13.1	13.3	13.0	13.1
2208	5 January 2017	11.4	11.4	11.2	12.0	11.7	11.4
4368	5 April 2017	11.5	11.4	11.5	11.3	11.4	11.4
6552	5 July 2017	11.2	11.4	11.3	11.8	11.8	11.3
8760	5 October 2017	11.1	11.4	11.4	11.2	11.4	11.4
10968	5 January 2018	11.3	11.4	11.1	11.5	11.6	11.4
13128	5 April 2018	11.2	11.4	11.5	11.6	11.8	11.6
15312	5 July 2018	11.5	11.4	11.2	11.6	11.5	11.5
17520	5 October 2018	11.4	11.4	11.3	11.3	11.5	11.4
19728	5 January 2019	11.2	11.4	11.3	11.4	11.3	11.3
21912	5 April 2019	11.5	11.4	11.1	11.4	11.2	11.2

Table 5. Measured elongation after break of 22kV TR-EPR cable from long term endurance test

Time	Date			Elongation (10%)			Median
				Sample			
		1	2	3	4	5	
Initial	5 October 2016	425	420	450	450	430	430
2208	5 January 2017	397	386	388	381	372	386
4368	5 April 2017	391	385	395	386	374	385
6552	5 July 2017	378	384	379	390	387	384
8760	5 October 2017	379	390	384	392	385	385
10968	5 January 2018	386	380	390	386	379	386
13128	5 April 2018	384	388	381	384	388	384
15312	5 July 2018	381	387	381	384	378	381
17520	5 October 2018	381	382	381	384	373	381
19728	5 January 2019	384	380	376	377	373	377
21912	5 April 2019	371	384	389	378	378	378

Results show that TR-EPR is in conformity with the standards of Hot set test except for the delayed development of cross-linking: about 5 days at 60ºC and 24 days at ambient temperature. It should be noted that Hot set test is usually performed to verify completion of cross-linking [14] and that cross-linking is associated with reduction of treeing phenomenon which is a long-term development. Hence it becomes a reasonable proposal for the acceptance of installing TR-EPR cables without prior passing to the Hot set test as the argument for the purpose of doing so is achieved in a later time during the operation of the cable. Additionally, the manufacturer actually performs accelerated cross-linking through exposure of sample insulation at 90ºC for 24 hours prior to being released in the market. Since the insulation has been heated at a significantly higher temperature (90ºC) than what was performed in this paper (60ºC), the cross-linking is achieved at a significantly shorter span of time about 24 hours.

5. CONCLUSIONS

TR-EPR proved to be a promising option for underground cabling distribution lines being a significant development of EPR in terms of much lower dielectric losses compared to XLPE. The cost of TR-EPR is also reduced by using silane curing method. Cross-linking of silane-cured TR-EPR is achieved for the following conditions: 24 days at ambient temperature and 5 days at 60ºC. Mechanical properties of the material show stability and consistency through-out the ageing period of 30 months. There is also improvement of the partial discharge to acceptable low values after heating. The results of long-term thermal aging in this paper open up an opportunity to model the thermal life of TR-EPR cable.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Victoria University for granting the scholarship for this research project.

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