

A Novel Approach for Estimating the Service Lifetime of Transformers within Distributed Solar Photovoltaic (DSPV) Systems

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ABSTRACT

The rapid transformation of the energy sector in South Africa towards renewable energy (RE) production calls for the management of assets to keep pace with the ongoing developments in a reliable manner. Aging assets, increasing energy needs and reliable supply of energy without load shedding are some of the challenges utilities are facing in South Africa. In resolving these challenge, imaginative solutions are required to maintain the installed assets and determining the viability of refurbishment, replacement or upgrading. In the current work, an extension of the author's previous work, a novel approach for estimating the service lifetime of transformers within Distributed Solar Photovoltaic (DSPV) Systems in South Africa is introduced. This experiential form has been derived by extensive experimental trials. The proposed approach is initially employed to evaluate the Degree of polymerization (DP) of cellulose insulation based on measured furan (2FAL) contents of 9 case scenarios. The calculated DP is then used to evaluate the service lifetime of these units. In efforts to authenticate the proposed approach, a comparative study is conducted against 5 other models. Finally, the proposed approach is compared with the results of the measured DP. It is observed that the proposed approach produce accurate estimates with an approximation not exceeding 1% and 2.2% from the measured DP and service lifetime respectively.

1. Introduction

Oil-immersed Distributed Solar Photovoltaic (DSPV) system transformers are commonly designed for a service lifetime of about 30 years [1], [2]. During service, the cellulose insulation degrades under the interactive effects emanating from electrical, thermal and chemical components. The mechanism of degradation of cellulose insulation (DCI) is reliant on the conditions such as harmonics, distorted load cycle and excessive heating that the transformer may be subjected to during their designed service lifetime. There are four underlying factors that elevate the DCI viz. moisture, oxygen, acid and excessive temperature. The oil-cellulose insulation system in DSPV transformers is prevalent on account of its cost-effectiveness and capacity to withstand severe electrical and thermal stresses [3], [4]. Due to the costly exercise of replacing field transformers, the utility owners will keep the units in service while performing periodical online monitoring and routine testing of the insulation system. Therefore, diagnostic techniques suchlike Dissolved Gas Analysis (DGA) and Furan Analysis (FA) are increasingly being recognized as efficacious and irrefutable

procedures to evaluate the reliability of oil-cellulose insulation system.

The chemical structure of cellulose insulation is composed of strings of anhydroglucoses linked via glycosidic bonds [5] – [7]. These bonds have relatively low temperature resistance in relation to hydrocarbon bonds prevailing in DSPV transformer oil [8]. This degradation phenomenon triggers depolymerisation which leads to degraded forms of glucose as shown in Figure 1 [9]. The formation of glucose will further degrade to forge furans, water and combustible gases [9 – 11].

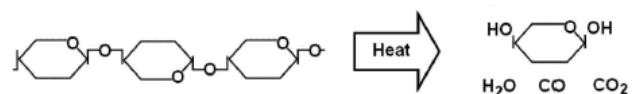


Figure 1: Thermal degradation of cellulose insulation

The generation of Furan compounds (FCs) is distinctly on the cellulose insulation and seemed to be kind of stable at elevated

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temperatures reaching 140°C within the transformer oil [12]. The existence of FCs remains in oil-immersed transformers even at elevated temperatures geared towards providing a divulgence to the condition of the cellulose insulation.

The FCs 2-FAL, 5-hydroxymethyl-2-furaldehyde, 2-acetylfuran, 5-methyl-2-furaldehyde, and 2-furfuolare are the most widely known in the transformer manufacturing industry. The FC 2-FAL is most widely-used in the industry relating its content to the cellulose degree of polymerization (DP) which is the number of monomeric units in the cellulose polymer [13] – [14]. Furans are a constituent of the products of degradation of the transformer cellulose insulation. During service, they are moderately dissolvable in the transformer oil. The relationship between the transformer state and the concentration of the furan content in the oil is as shown in Table below.

Table 1: 2FAL concentration criterion

Status	Concentration [in ppm]
Healthy	2FAL < 0.5
Satisfactory	0.5 ≤ 2FAL ≤ 1
Warning	1.1 ≤ 2FAL ≤ 1.5
Poor	1.6 ≤ 2FAL ≤ 2
Extremely poor	2FAL ≥ 2.1

In the current work, an extension of the author’s previous work [14], a novel approach for estimating the service lifetime of transformers within DSPV Systems in South Africa is introduced. This experiential form has been derived by extensive experimental trials. The proposed approach is initially employed to evaluate the DP of cellulose insulation based on measured 2FAL contents on a fleet of selected case scenarios. The calculated DP is then used to evaluate the service lifetime of these units. In efforts to authenticate the proposed approach, a comparative study is conducted against 5 other models. Finally, the proposed approach is compared with the results of the measured DP. It is observed that the proposed approach produce accurate estimates with an approximation not exceeding 1% and 2.2% from the measured DP and service lifetime respectively.

2. DP Models

In this day and age, the aging condition of transformers can be established by mathematical modelling which launch the relationship between furan concentrations, DP, and transformer service lifetime.

2.1. Existing DP models

Several authors in [15] - [19] have established mathematical formulae which relate the furan concentrations and the measure of the DP of the insulation material. An illustration of this relationship based upon this methods is presented in Figure 2. A Further in [20], mathematical formulae has been developed to describe the relationship between DP and the service lifetime. In order to attain a thread that binds the furan concentrations and the DP of the cellulose insulation (CI), the DP methods are compared at different furan contents. The comparison indicate that the methods can evaluate the DP ranging from 1 to 14.

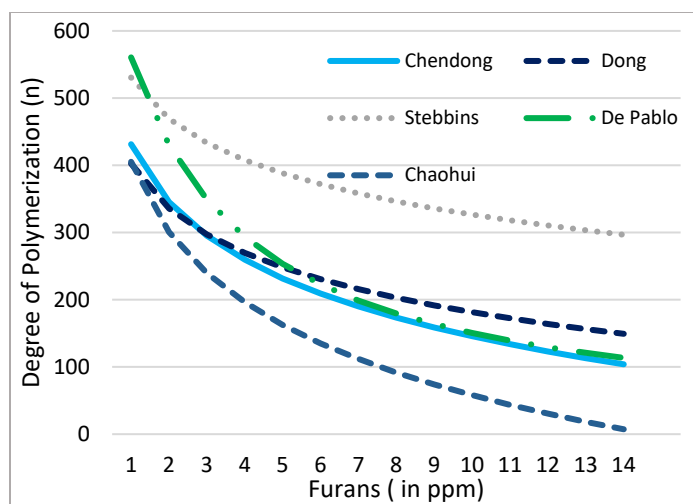


Figure 2: Correlation between the DP and Furans (2FAL)

The development, identification and behaviour of furan compounds has been described by [21], [22] and [23]. In the next sub-section a comprehensive description of the model proposed in this work is presented.

2.2. Proposed model

Based upon observational data, a fleet of mineral oil samples were analysed to develop a novel DP model for transformers serving exclusively in distributed solar photovoltaic systems. The proposed model can be applied to ascertain the DP of cellulose insulation with accuracy following 2-FAL measurement in the oil. The proposed model is as shown in Eq. (1) below.

$$DP = 763.67 - 584.23x + 398x^2 - 135.52x^3 + 17.14x^4 \quad (1)$$

Here,

$$x = 2\text{-FAL}$$

The concentration (in ppm) of the furan content 2-FAL can be easily substituted in the formulae to obtain the DP of a transformer.

2.3. Transformer Service Lifetime

The transformer age can be obtained by applying Eq. (2) and Eq. (3) below [20]. With the knowledge of the DP of the transformer, the service lifetime can be ascertained.

$$Service\ lifetime(in\ years) = 20.5 \ln\left(\frac{1100}{DP}\right) \quad (2)$$

$$\%Life\ used = \frac{\log_{10}(DP) - 2.903}{-0.006021} \quad (3)$$

3. Case Scenario

In this section, the 2FAL results of 9 mineral-oil immersed DSPV transformers are considered. The gas concentrations are obtained from oil samples collected from various DSPV facilities. The studied transformers range from 100kVA to 20 000 kVA as shown in Table 2.

Table 2: Case Studies

Case	Rating (kVA)	Voltage (kV)	2FAL
A	1500	6.6/0.5	1.778
B	1500	6.6/0.5	2.377
C	100	0.525/0.4	3.00
D	150	0.525/0.4	1.601
E	20 000	6.6/0.5	0.676
F	20 000	6.6/0.5	0.231
G	20 000	88/6.6	0.143
H	4000	6.6/0.5	1.513
I	2000	6.6/0.5	1.563

The 2-FAL contents were measured during the routine maintenance of the transformers.

3.1. Degree of Polymerization

In order to determine the accuracy of the formulae presented by the authors in [15] – [19] and the proposed formula in the current work, the DP for the studied cases are evaluated and tabulated as a shown in Table 3 below. Stebbins [18] results are observed to yield a significantly protruding DP values compared to all the other methods.

Table 3: DP of studied transformers using furan compounds (2FAL)

Case	2FAL	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chao hui [19]	Proposed
A	1,778	360	454	347	480	318	393
B	2,377	324	396	319	454	275	351
C	3	295	349	297	433	240	322
D	1,601	373	474	357	489	334	405
E	0,676	480	622	440	565	464	512
F	0,231	613	731	543	660	626	648
G	0,143	673	757	589	703	699	688
H	1,513	380	485	363	494	343	411
I	1,563	376	479	360	491	338	408

These DP values are a measure of the realistic aging of the cellulose insulation, which governs the transformer’s service lifetime. And so, it is possible to evaluate the service lifetime of a transformer and make comparison with real life by means of furan concentration within the oil. The latter improves the assessment of the reliability of service transformers.

3.2. Transformer Service Lifetime

Further to previous sub-section, the remaining service lifetime of the studied cases is determined using the DP results as presented in Table 4 for all models.

Table 4: Remaining service lifetime estimation

Case	2FAL	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chao hui [19]	Proposed
A	1,778	22,90	18,16	23,64	17,02	25,41	21,12
B	2,377	25,06	20,97	25,35	18,15	28,44	23,43

Case	2FAL	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chao hui [19]	Proposed
C	3	26,97	23,53	26,84	19,10	31,25	25,18
D	1,601	22,17	17,25	23,05	16,62	24,42	20,49
E	0,676	17,00	11,70	18,78	13,65	17,68	15,66
F	0,231	11,98	8,38	14,47	10,46	11,55	10,84
G	0,143	10,08	7,65	12,80	9,18	9,31	9,62
H	1,513	21,79	16,78	22,74	16,41	23,90	20,17
I	1,563	22,01	17,05	22,92	16,53	24,20	20,35

The relationship between the DP and the service lifetime is illustrated by Figure 3 below.

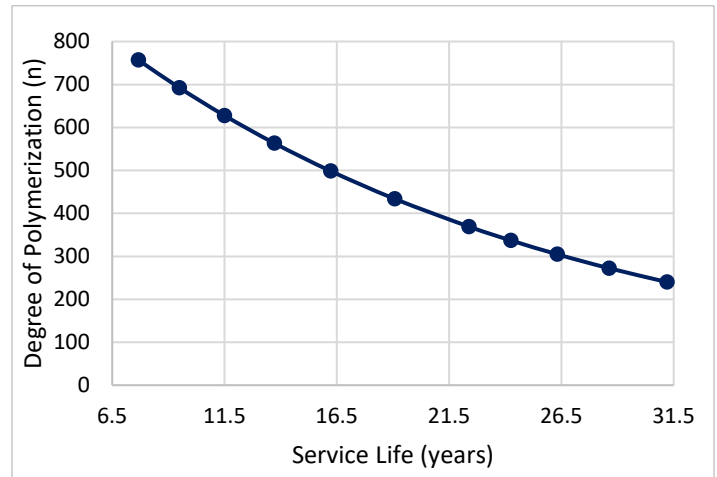


Figure 3: Correlation between the DCI and Furans (2FAL)

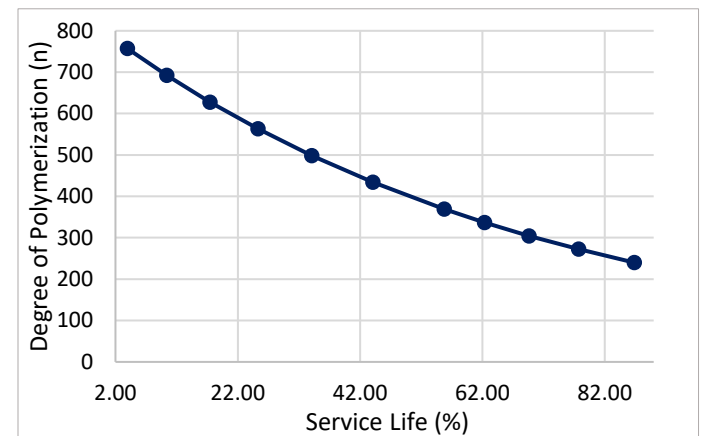


Figure 4: Correlation between the DP and %Service lifetime

It can be observed that as the transformer life is service is longer, the DP decreases. In Table 5, the percentage of the service lifetime for all cases is presented.

Table 5: Percentage of transformer service lifetime

Case	2FAL	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chao hui [19]	Proposed
A	1,778	57,58	40,90	60,18	36,89	66,42	51,32
B	2,377	65,18	50,79	66,21	40,87	77,09	59,46
C	3	71,92	59,81	71,44	44,22	86,95	65,61

Case	2FAL	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chaohui [19]	Proposed
D	1,601	55,02	37,70	58,12	35,51	62,93	49,10
E	0,676	36,83	18,18	43,10	25,03	39,23	32,13
F	0,231	19,16	6,50	27,93	13,81	17,65	15,15
G	0,143	12,48	3,94	22,07	9,31	9,77	10,88
H	1,513	53,67	36,06	57,03	34,77	61,11	47,98
I	1,563	54,44	37,00	57,66	35,19	62,15	48,62

The percentage of service lifetime is observed to correlate with the data presented in Table 4. The correlation between the DP and the percentage service lifetime is illustrated by Figure 4.

It is observed that the DP decreases with respect to the aging of the transformer.

3.3. Practical Results

In this subsection, the values of the measured DP and 2FAL of the nine studied transformers that operate in various DSPV systems are presented in Table 6.

Table 6: Percentage of service lifetime

Case	2FAL	Measured DP	Service Life	% Service Lifetime
A	1,778	389	21,30	51,96
B	2,377	352	23,35	59,16
C	3	322	25,20	65,67
D	1,601	404	20,56	49,35
E	0,676	515	15,57	31,78
F	0,231	641	11,08	15,99
G	0,143	694	9,46	10,29
H	1,513	412	20,15	47,92
I	1,563	411	20,20	48,10

3.4. Results comparison

The error of estimation for DP, service lifetime and percentage service lifetime against the measured results are presented in this subsection for the studied DSPV transformers. In Table 7, it can be observed that the proposed formula gives an accurate estimation of the DP in comparison to the other models across all nine cases.

Table 7: Error of estimation: DP

Case	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chaohui [19]	Proposed
A	7,5%	16,6%	10,8%	23,2%	18,2%	0,88%
B	8,0%	12,3%	9,3%	28,9%	22,0%	0,42%
C	8,3%	8,5%	7,7%	34,6%	25,5%	0,09%
D	7,6%	17,5%	11,4%	21,2%	17,2%	0,36%
E	6,8%	20,8%	14,5%	9,8%	9,8%	0,48%
F	4,3%	14,1%	15,3%	3,1%	2,3%	1,17%
G	3,0%	9,2%	15,1%	1,4%	0,7%	0,81%
H	7,7%	17,9%	11,9%	20,0%	16,7%	0,09%
I	8,4%	16,6%	12,4%	19,6%	17,7%	0,72%

It is observed that the proposed formula produces accurate estimates with an approximation not exceeding 1% from the www.astesj.com

measured DP. As a result, it is evident that the proposed formula achieves a higher accuracy. In Table 8, the error of estimation of the calculated and measured results of the service lifetime is presented.

Table 8: Error of estimation: Service Life

Case	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chaohui [19]	Proposed
A	7,5%	14,7%	11,0%	20,1%	19,3%	0,85%
B	7,3%	10,2%	8,6%	22,3%	21,8%	0,37%
C	7,0%	6,6%	6,5%	24,2%	24,0%	0,07%
D	7,8%	16,1%	12,1%	19,1%	18,8%	0,35%
E	9,2%	24,8%	20,7%	12,3%	13,6%	0,64%
F	8,1%	24,4%	30,6%	5,6%	4,3%	2,16%
G	6,6%	19,1%	35,4%	2,9%	1,6%	1,77%
H	8,1%	16,7%	12,9%	18,5%	18,6%	0,09%
I	8,9%	15,6%	13,5%	18,2%	19,8%	0,74%

It is observed that the proposed formula produce accurate estimates with an approximation not exceeding 2.2% from the measured service lifetime.

Table 9: Error of estimation: % of transformer service life

Case	Chendong [15]	De Pablo [16]	Dong [17]	Stebbins [18]	Chaohui [19]	Proposed
A	10,8%	21,3%	15,8%	29,0%	27,8%	1,22%
B	10,2%	14,2%	11,9%	30,9%	30,3%	0,51%
C	9,5%	8,9%	8,8%	32,7%	32,4%	0,10%
D	11,5%	23,6%	17,8%	28,1%	27,5%	0,52%
E	15,9%	42,8%	35,6%	21,2%	23,4%	1,10%
F	19,8%	59,4%	74,7%	13,7%	10,4%	5,27%
G	21,3%	61,7%	114,5%	9,5%	5,1%	5,71%
H	12,0%	24,8%	19,0%	27,4%	27,5%	0,13%
I	13,2%	23,1%	19,9%	26,8%	29,2%	1,09%

It is observed that the proposed formula produce accurate estimates with an approximation not exceeding 5.8% from the measured percentage service lifetime.

At large, the overall assessment of the proposed formula presented in this work presented the highest precision in the estimation of the DP of the cellulose insulation in comparison to the other 5 models.

4. Conclusion

The knowledge of the transformer service lifetime and the specific point in time that is suitable to replace transformers is critical for utility owners. These determinations are dependent upon the condition of the cellulose and liquid insulation. In practical terms, knowledge on the condition of insulation is crucial to undertake adequate life cycle and reliability management of transformers in the facility. In the transformer industry, the physical chemistry of oil is prevalent in the evaluation of the transformer life cycle considering that oil samples can easily be extracted at site to the laboratory for analysis.

In the current work, an extension of the author's previous work [14], a novel approach for estimating the service lifetime of transformers within DSPV Systems in South Africa was introduced. This experiential form has been derived by extensive experimental trials. The proposed approach was initially employed to evaluate the DP of cellulose insulation based on measured 2-FAL contents (in ppm) of 9 case scenarios. The calculated DP was then used to evaluate the service lifetime of these units. In efforts to authenticate the proposed approach, a comparative study was conducted against 5 other models. Finally, the proposed approach was compared with the results of the measured DP. It was observed that the proposed approach produce accurate estimates with an approximation not exceeding 1% and 2.2% from the measured DP and service lifetime respectively.

In future work, the authors will test the proposed formula with other different transformers. Further, the authors will carry out work related to the reliability analysis of DPSV transformers based upon their operating hours in service by apply the Weibull distribution technique and support vector machine to classify their reliability.

Conflict of Interest

The authors declare no conflict of interest.

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