

Lessons Learned from Analysis of Power Transformer Failure Rates

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Abstract— This work is a compilation of lessons learned from the analysis of power transformer failures occurred in North and South America based on data collected by Doble Engineering Company over the last ten years. The paper includes annual failure rates and related reports based on voltage rating, failure cause, manufacturing decade, age distribution, among other parameters.

Keywords—transformer, failure rate, failure cause, age distribution.

I. INTRODUCTION

Historically, Doble Engineering Company (Doble) had collected transformer failure records without knowing the associated failure rates since the transformer population data — needed to compute the failure rates — was not provided by its clients. The typical practice was to simply tabulate every year all the reported failures so that clients could use this information to determine a trend of failures on a particular transformer brand/type. A more thorough work began nine years ago with some utilities asking Doble for a benchmark to compare their transformer failure rates with others in the industry in order to evaluate their own performance. Furthermore, they wanted to trend their failure rates from year to year. As a result, Doble started requesting the population data in addition to failure records.

The project was initiated with three participants. Currently, it has grown to 40 utilities from North and South America with a total population of more than 50,000 transformers and 3,858 reported failures, and manufacturing years spanning from early 1900s to 2022, which includes more than 200 transformer manufacturing brands. Fig. 1 shows the historical growth of the database. The blue bars correspond to the participating utilities, the white curve to the total transformer population and the yellow bars to the reported failures.

The Doble Transformer Failure Statistics Sub-committee was created to ensure the sustainability of this project. As a result, in addition to originally providing a listing of their transformer population and historical failure records, the participants have kept submitting their annual updates, which include their recent failures, newly installed and retired transformers. These last three sets of data are needed to maintain accurate annual failure rate calculations.

This paper is a compilation of lessons learned from the analysis of power transformer failures occurred in North and

South America based on data collected by Doble over the last nine years. The work includes annual failure rates and related reports based on voltage rating, failure cause, manufacturing decade, age distribution, among other parameters.

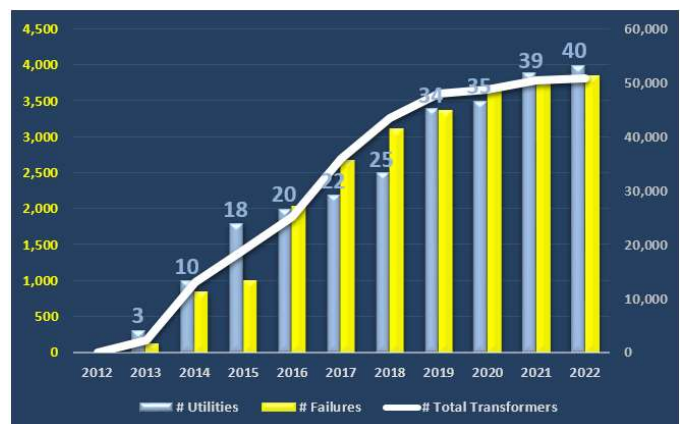


Fig. 1. Historical database statistics.

II. DEFINITION OF TRANSFORMER FAILURE

The general failure definition adopted by the sub-committee is that the transformer fails when it is determined that it needs to be removed from the pad. However, there are some aspects to be considered in order to provide a correct interpretation of a failure, as explained next. This allows maintaining a consistent interpretation approach so that comparisons can be performed under similar conditions.

For example, if the transformer was generating high levels of combustible gasses, and:

- The client degassed and returned it to service; it *is not considered to be a failure* so that the transformer will remain in the total in-service population.
- The client determined that it is unsafe to remain in service; it *is considered to have failed* so that it will be removed from future annual in-service population totals.
- The client determined that the unit is too old to warrant an investigation; it *is not considered to be a failure* but rather a scrapped/retired transformer so that it will not be included as part of the failure rate calculation but will be removed from future annual in-service population totals.

In the case of a bushing failure:

- If a bushing fails and it causes the transformer to fail, we consider it a transformer failure with the cause being the bushing failure.
- If a bushing fails and the transformer can be cleaned with the bushing replaced and reenergized, it is not a transformer failure.
- If the bushing failure resulted in so much contamination that the transformer could not be cleaned and returned to service, it is considered a transformer failure with the cause being the bushing failure.

The same logic applies to Load Tap Changer (LTC) and De-energized Tap Changer (DETC) problems. Assuming that the problem is repairable on site, this is not a failure. However, if the investigation determines that the transformer needs to be removed from the pad and returned to the factory to be fixed, then we would consider it a failure.

As for a scrapped/retired transformer, it is one that is removed from the pad for business/financial/inadequate loading capacity reasons and did not exhibit signs of a problem. This is not considered a failure.

Finally, if a transformer fails and is rebuilt, it is considered to be a new transformer even though the serial number may be reused. Under these conditions, there will be duplicate serial numbers in the database: one will be associated with the transformer failure using the original manufacturing date and the other with the same transformer listed as in-service with a manufacturing date linked to the date when it was rebuilt.

III. FAILURE RATES

A. Annual Failure Rates

The annual failure rate is calculated by dividing the total number of failures in a specific year by the total number of in-service transformers in that same year as shown in (1):

$$\text{Annual Failure Rate} = \frac{\# \text{ failures}}{\text{Total in-service units}} \times 100\% \quad (1)$$

The total in-service transformer population in a specific year is equal to the total transformer population in the database minus those that have failed and have been retired/scrapped in previous years. For example, a transformer that failed in 2012 would be included in the in-service transformer population for years ≤ 2012 but excluded from the 2013 (and beyond) calculations. Likewise, transformers manufactured in 2013 would not be included in the total population for years ≤ 2012 .

Fig. 2 summarizes the annual failure rates for 40 utilities during the past seven years (failure rates from previous years starting with 1950 can be found in [1], where a smaller database was used). We have kept anonymously the names of the participants by identifying them with a numeric ID, where IDs from 36 to 39 correspond to participating utilities from South America, while the rest from North America. Below the ID (in parentheses) there is their actual in-service population size, which enables participants to compare their failure rates with utilities of similar size in addition to comparing their own annual failure rate trend from year to year and with the overall failure rate of all the participants (second column). Empty cells indicate that no failure data was provided for that specific year. A “zero” indicates that the client reported to have no failures in the specific year.

The overall failure rate column is based only on participants who provided data for the corresponding year. Observe that the overall failure rate in the past seven years varies from 0.32% to 0.56%. However, it is worth noting that for the last two years, i.e., 2020 and 2021, it has been difficult to collect the data updates from some participants due to COVID pandemic limitations. A random pattern of failure rates is observed when we look chronologically at the entries of each client’s column, which makes us think whether it is actually due to a random chance or because other variables play an important role, e.g., weather variations, loading profiles, changes in maintenance practices, asset management strategy, testing, or purchasing patterns.

Year	Overall Failure Rate [%]	Average Service Age [Years]	Client ID and (In-service Population Size)																				
			Client 1 (1371)	Client 2 (474)	Client 3 (2030)	Client 4 (523)	Client 5 (164)	Client 6 (423)	Client 7 (1023)	Client 8 (5226)	Client 9 (1595)	Client 10 (2237)	Client 11 (330)	Client 12 (357)	Client 13 (6397)	Client 14 (2424)	Client 15 (2025)	Client 16 (220)	Client 17 (141)	Client 18 (159)	Client 19 (174)	Client 20 (2343)	
2021	0.56	40	0.62			0.38															0	0	
2020	0.32	39	0.6			0.56									0.27		0.08				0	0	0.17
2019	0.35	38	0.51			0.37		0.7		0.02	0.13			0	0.17	0.49	0.39	0		0.62	0.57	0.30	
2018	0.46	37	0.74			1.5		0.47	0.29	0.25	0.25	0.13		0.27	0.24	0.61	0.87	0.43	1.39	0.61	0.58	0.35	
2017	0.47	37	0.89	0.21		0		1.17	0	0.11	0.43	0.22	1.21	0.27	0.27	1.21		0.84	0.68	0.60	1.74	0.13	
2016	0.41	36	0.47	0.63		0.38		0.47	0.39	0.08	0.68	0.14	0	0.27	0.09	1.23		0.82	1.39	2.27	1.75	0.31	
2015	0.40	36	0.97	0.85		0.75	0.57	0.94	0.59	0.06	0.31	0.41	0	0.55	0.19	0.67		0.84	0	1.12	0.59	0.22	

Year	Overall Failure Rate [%]	Average Service Age [Years]	Client ID and (In-service Population Size)																			
			Client 21 (935)	Client 22 (2034)	Client 23 (2675)	Client 24 (425)	Client 25 (456)	Client 26 (27)	Client 27 (762)	Client 28 (433)	Client 29 (117)	Client 30 (179)	Client 31 (646)	Client 32 (1629)	Client 33 (482)	Client 34 (181)	Client 35 (423)	Client 36 (21)	Client 37 (197)	Client 38 (24)	Client 39 (710)	Client 40 (220)
2021	0.56	40	0.63							0.23				0.56			0	0	0	0	0	0.90
2020	0.32	39	0.42	0.44		0				0					0.21		0.24	0	0.51	0	0	0
2019	0.35	38	0.31	0.45	0.95	0.23	0.43		0.26	0.46				0		0.61		0.24	0			0
2018	0.46	37	0.52	0.25	0.68	0	0	0	0.26	0.23				0	1.33	0.52	0	0				0
2017	0.47	37	0.42	0.30	0.60	0	0.22	0	0.77		0.78	0		0.37	0.56	0.54	0	0				0.93
2016	0.41	36	0.75	0.15	0.63	0.24	0.22	0		0.72		0.56	0.15	0.43	0.19			4.55				0.47
2015	0.40	36	0.54	0.60	0.28		0.44	0	0.13			0	0.92	0.06	0.38			4.35				0

Fig. 2. Annual failure rates (%) from 40 utilities.

B. Probability Distribution of Annual Failure Rates

Fig. 3 and Fig. 4 show the probability distribution of the annual failure rates of the participating utilities for years 2018 and 2019, respectively, based on the data shown in Fig. 2. Each data point has been identified with the corresponding numeric client ID. The area under an infinitesimally small interval in the curves of the probability density function can be used to determine the probability (likelihood) of the failure rate falling within the corresponding infinitesimally small range of values. The probability would be higher around the range of failure rates having a higher probability density value as long as the infinitesimally small intervals that are taken over the whole curve are all of the same size.

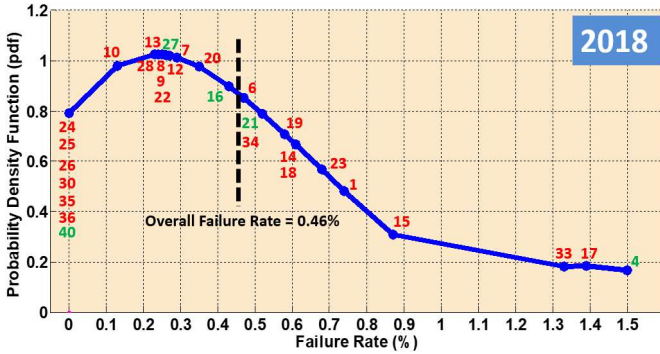


Fig. 3. Probability distribution of annual failure rates in 2018.

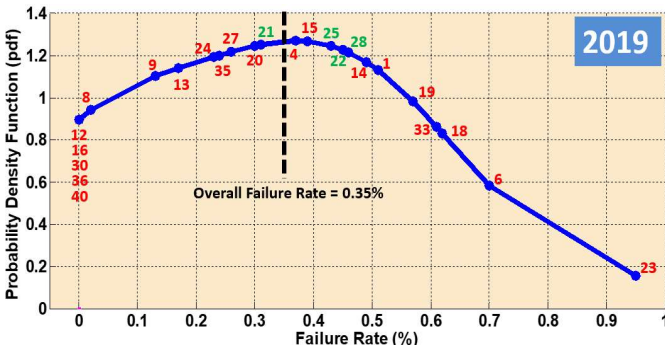


Fig. 4. Probability distribution of annual failure rates in 2019.

It is observed that in 2018 (Fig. 3), the overall failure rate of the whole database (i.e., 0.46%, as shown in Fig. 2) is located to the right of the maximum of the probability density curve (i.e., 0.24%). The latter corresponds to the most likely failure rate to be sampled (i.e., the mode) among the participating utility clients in 2018. Unlike the 2018 curve where the data seems to be more disperse and concentrated to the left, the 2019 curve is more symmetrical resulting in the mode almost coinciding with the overall failure rate of 0.35%. In all cases, if we chose the overall failure rate as a benchmark for comparison, it would mean that any data point to the left of it would have had a better performance in their annual failure rate since it is lower than the benchmark.

C. Failure Rates Based on High-Voltage Winding Rating

The failure rates are classified in four high-voltage winding rating segments based on [2]: distribution, sub-transmission, transmission (high voltage) and transmission (extra high voltage). Fig. 5 shows the failure rates for years 2015 through 2020 corresponding to voltage rating category.

Failure Rates (%)							
High-Voltage Winding Rating		Year 2015	Year 2016	Year 2017	Year 2018	Year 2019	Year 2020
Distribution	$5 \leq kV < 15$	0.78	1.02	1.53	1.13	7.14	No data
	$15 \leq kV < 25$	0.39	0.39	0.46	0.33	0.40	No data
	$25 \leq kV < 35$	0.29	0.22	0.28	0.29	0.32	0.34
Sub-Transmission	$35 \leq kV < 45$	0.18	0.27	0.09	0.92	0.31	2.50
	$45 \leq kV < 69$	0.49	0.72	0.68	0.69	0.61	0.59
	$69 \leq kV < 115$	0.52	0.54	0.66	0.55	0.40	0.46
Transmission (HV)	$115 \leq kV < 230$	0.61	0.49	0.56	0.45	0.45	0.35
	$230 \leq kV < 345$	0.95	1.20	1.28	0.92	1.29	0.77
Transmission (Extra HV)	$345 \leq kV < 500$	2.34	1.36	0.93	1.03	1.91	0.81
	$500 \leq kV < 765$	1.70	0.96	1.07	1.42	3.70	0.86

Fig. 5. Failure rates per voltage rating category.

For each year, the relationship between failure rate and high-voltage winding rating is depicted in Fig. 6. It is observed that, in general, in the distribution segment the failure rates start with a higher value at the $[5 \leq kV < 15]$ category followed by a decreasing behavior as the voltage rating increases. Several factors may play a role in causing this higher failure rate at the lowest voltage rating. For instance, one of them could be the run-to-failure (RTF) maintenance strategy employed by some utilities for these smaller units. In addition, these units might be subjected to less advanced design techniques given their low cost of manufacturing in comparison with larger units. As a result, their failure rate would become higher by being exposed to more system disturbances

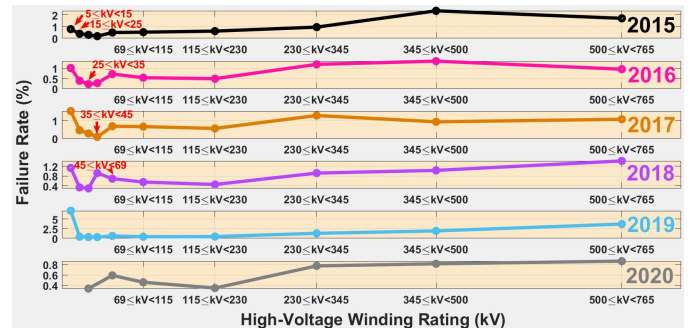


Fig. 6. Failure rate vs. high-voltage winding rating.

The sub-transmission segment shows a more constant pattern of failure rates versus voltage rating. Meanwhile, for the transmission (HV) segment, it is observed that the failure rates increase as the voltage rating increases. On the other hand, the transmission (EHV) segment shows a decreasing behavior of the failure rates as the voltage rating increases for years 2015 and 2016. The inverse is observed for years 2017 through 2020.

IV. OTHER RELATED REPORTS

A. Reported Causes of Failures

In many cases, transformer failures occur without knowing the cause that initiated them. Sometimes, resources are not available to conduct a detailed investigation into the cause. Understanding the cause of failures is the first step in developing a strategy to prevent them. Fig. 7 shows a characterization of the reported causes of failures in our database. It is observed that the “Winding/Shorted Turn” category is the most prevalent event among the reported causes of transformer failures, followed by “Other” in second place and “Bushing” closely in third place. Similar results were reported in [3]. The “Other” category combines several failure causes that individually represent a low percentage, e.g., vandalism, overload, oil leak, cooling loss, tank, etc.

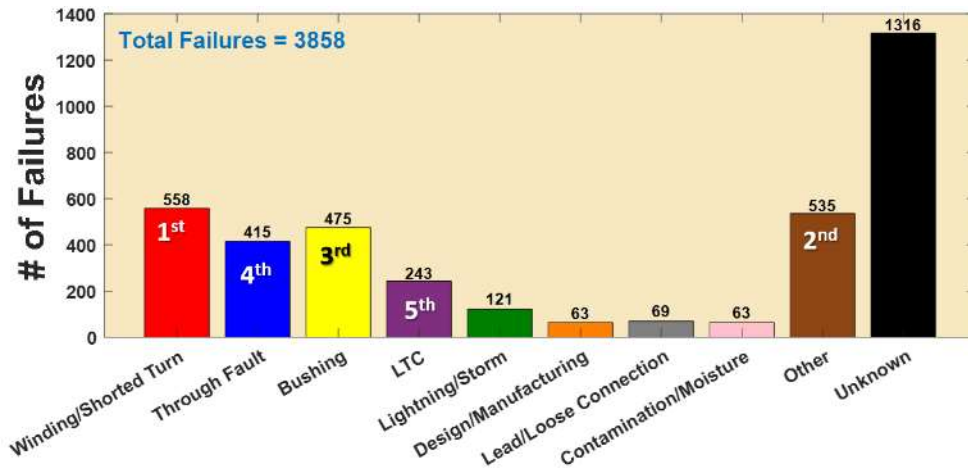


Fig. 7. Characterization of the reported causes of failures.

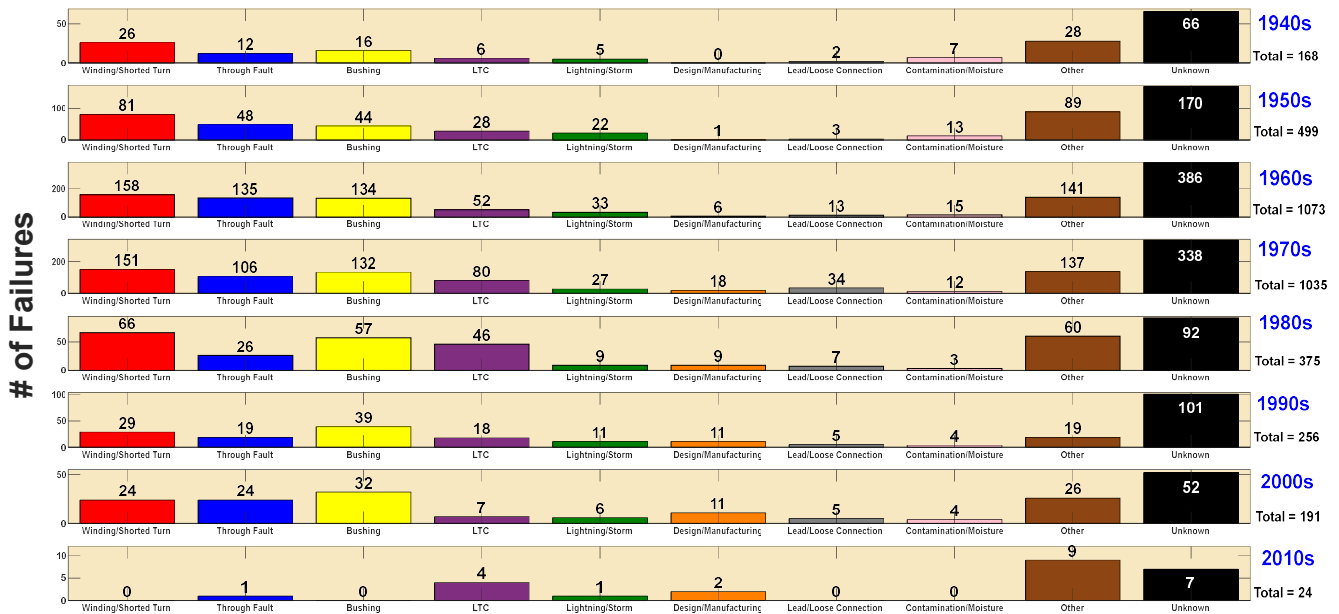


Fig. 8. Reported failure causes based on transformer manufacturing decade.

Fig. 8 summarizes the distribution of failure causes according to the transformer manufacturing (MFR) decade. The following can be inferred from the graph:

- “Winding/Shorted Turn” and “Other” are the most prevalent events among the reported failure causes for transformers manufactured in 1940’s and 1950’s followed by “Through Fault” and “Bushing”.
- “Winding/Shorted Turn” remained the most prevalent cause of failure for transformers with MFR decade in 1960’s and 1970’s followed by “Other”, “Bushing” and “Through Fault” being close to each other.

- For transformers with MFR decade in 1980's, "Winding/Shorted Turn" is still the number one cause of failure followed by "Other" and "Bushing". Meanwhile, "Through Fault" is no longer a leading cause; it occupies the fifth position with LTC taking the fourth place.
- For transformers with MFR decade in 1990's and 2000's, the scenario seems to change for "Winding/Shorted Turn" since "Bushing" is now the most prevalent reported cause of failure followed by "Winding/Shorted Turn", "Other" and "Through Fault".
- Data for MFR decade in 2010's is not yet sufficient to draw conclusions.

Failure cause results based on transformer manufacturing decade per high-voltage winding categories can be found in [4].

B. Age Distribution

Fig. 9 and Fig. 10 show the current age distribution of the total in-service population of transformers in our database for North America and South America, respectively.

In particular, we observe that for North America the age distribution segment of 51-55-year-old represents the maximum percentage of in-service units. This is consistent with what was reported in [5], which stated that the yearly installment of large power transformers in the U.S. had a peak value in the 1970's, which corresponds to the aforementioned age segment as of today.

It is also worth noting that, according to our database, there has been a reduction in the number of new units put in service in North America during these last 5 years in comparison with other subsequent age segments since it only represents 2.6%.

As for South America, its maximum in-service age population segment corresponds to 41-45-year-old, with a relatively less aged population in comparison with North America, which shows significant amounts of units still in service for ages higher than 60-year-old.

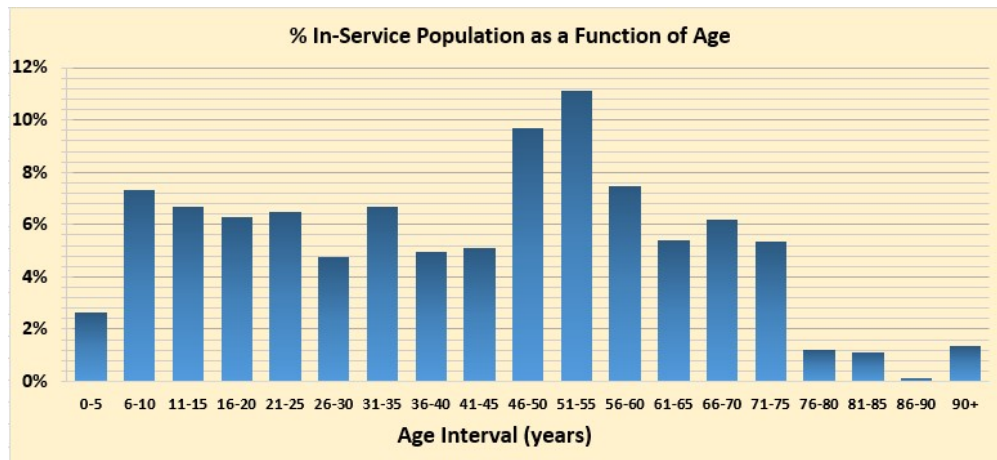


Fig. 9. In-service transformer age distribution for North America.

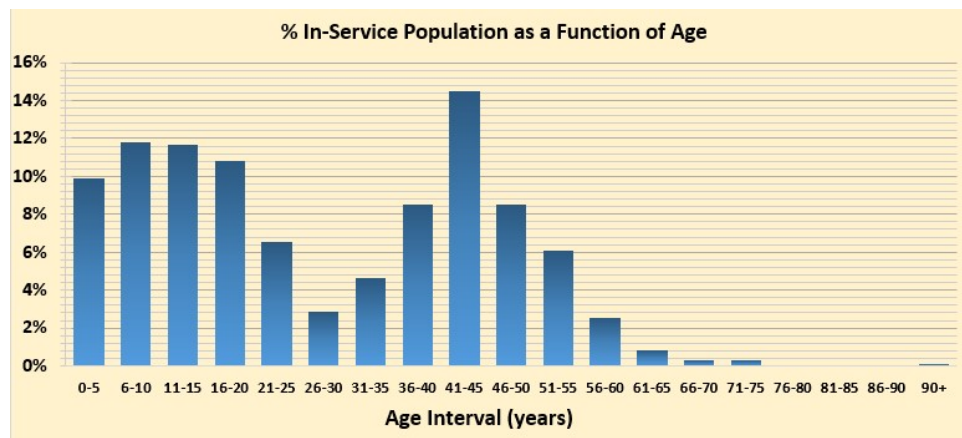


Fig. 10. In-service transformer age distribution for South America.

V. CONCLUSION

The database of the Doble Transformer Failure Statistics Sub-committee has experienced a sustained growth since its creation in 2013. As a result, its total population of approximately 50,843 transformers and associated 3,858 reported failures has allowed the participants to compare their annual failure rates with other utilities so that they can evaluate their performance. In addition, they can compare their own failure rate trend from year to year.

After breaking down the total annual failure rates into four high-voltage winding rating segments — distribution, sub-transmission, transmission (high voltage) and transmission (extra high voltage) — it was found that the voltage rating of $[5 \leq \text{kV} < 15]$ presented the highest failure rate among the voltage ratings in the distribution segment. On the other hand, for the transmission (HV) segment, it was observed that the failure rates increase as the voltage rating increases.

A comprehensive study of the transformer failure causes revealed that the “Winding/Shorted Turn” category is, in general, the most prevalent event among the total causes of reported transformer failures followed by “Other” in second place; “Bushing” closely in third place; “Through Fault”, fourth place and “LTC”, fifth place. Furthermore, the analysis of the failure causes based on the transformer-manufacturing decade shows that the most prevalent cause of failure is not always the “Winding/Shorted Turn” category, but there are instances where “Bushing” may dominate among the causes of failure, e.g., for transformers with MFR decade in 1990’s and 2000’s.

The age distribution of the in-service population shows a maximum for the age segment of 51-55-year-old in North America and 41-45-year-old for South America with the latter

region having a relatively less aged population in comparison with the former.

Finally, as the data keeps growing year to year, we expect to have more statistically significant conclusions and implementation of advanced techniques to develop failure probability models. We are committed to a long-term research project. Therefore, we expect more utilities from North and South America joining this effort.

ACKNOWLEDGMENT

The authors would like to thank the 40 utility clients participating in this project for their ongoing contributions. Their names are not listed to maintain their anonymity. In addition to originally providing a listing of their transformer population and historical failure records, they have kept submitting their annual data updates, which include their recent failures, newly installed and retired transformers. These last three sets of data are needed to maintain the accurate annual failure rate calculations.

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