10131 Session 2022
A2 – Power Transformers & Reactors
PS3 - Best Practices in Transformers and Reactors Procurement

Selection of high voltage bushings for transformers and shunt reactors considering local conditions – Brazilian transmission network case

Santhiago MONTENEGRO*[1] Nilton VIVEIROS[2] Yoshio NOMI[3] Roberto ASANO JR[4]
[1]CHESF [2]SIEMENS-ENERGY [3]HITACHI-ENERGY [4]UFABC
Brazil
santhiag@chesf.gov.br*

SUMMARY

Bushings are recognized as one of the more relevant primary cause of transformers and reactors failure and their reliability is directly related with the bushings function. Even a small malfunction on the bushing can lead to the unavailability of the associated transformer or reactor, which in some cases, has serious and expensive consequences. Critical failures can have even greater consequences, such as the explosion of the bushing, which can lead to the ignition of fire in the transformer and even leaving entire cities in blackout.
Although there are several evidences relating bushings with the impact on transformer reliability, it is rare to find an approach showing how the characteristics of the bushings selected during the transformer or reactor design stage impacts its long term performance in field.

National standards, in spite of being greatly influenced by international standards, may fail to adapt transformers and reactors bushings to local operational conditions, which are optimized to meet international standards requirements. While transformers are fully sized to every detail to comply with all characteristics of the local condition, bushing types available are conditioned by the global market, derived mostly from international standards. As a result, an eventual mismatch in the definition of the bushing characteristics with the transformer/reactor operational demands may lead to poor performance. When such details of the specification are not correctly taking into consideration, the bushing and the transformer/ reactor can be at risk. On the other hand, customized features or non-standard requirements may represent an extraordinary cost increase, since almost all the High Voltage bushings are standardized in categories by manufacturers. Consequently, the direct application of these standardized models can be, in some cases, challenging.

In Brazil, for instance, operation conditions are quite different from standard conditions specified by IEC (International Electrotechnical Commission). The differences start with a higher average ambient temperature and goes on up to specific overload requirements from the local system operator and regulator. Therefore, a Cigre-Brazil Task Force of SC A2 is evaluating this situation in order to collect experience and present to the local standardization council, aiming for improvements in the local standards. Several bushing manufacturers have been surveyed and their experiences collected together with the accumulated knowledge of large local users in a single document.

This article collects a summary of the Brazilian major transmission companies' requirements over its Extra-High Voltage and Ultra-High Voltage Transformers and Reactors bushings, and the result from the above mentioned survey, expressed through a guidance to consider local operation requirements in the specification of bushings for Transformers, Autotransformers and Shunt Reactors.

KEYWORDS
High Voltage Bushings, Technical Specification, overload

INTRODUCTION

Considering the role of power transformers and reactors in the energy industry, we may infer that bushings are important assets to that industry as well. This relevance may be overlooked on day-to-day basis, but a single failure in one bushing is enough to remind us of its importance.

As a well known potential cause of failures in power transformers, bushings reliability is a topic of general interest, especially for energy utilities, once their revenues are based on assets availability or power generated/transmitted. Brazilian utilities had and still have their share of problems related to the bushings. Those issues have been reflected directly on utilities policies, procurement, technical specification and maintenance or storage special procedures.

Motivated by the concern of the participants, Cigre-Brazil Mirror Study Committee A2 has organized a local Working Group (WG) focusing on the reliability of bushings for transformers and shunt reactors. Since that, this working group has been a hub for exchange of technical knowledge, transformer manufacturers, bushings manufacturers, academy and end users meet together to share hundreds of year of experience.

Two clear objectives were established for the WG: evaluate the failure rate of bushings used under the Brazilian grid demands and contribute to improve their reliability. The pursuing of this first aim is still ongoing, since the collection of data from bushing failure episodes has not been concluded. The second target has been partially achieved. Insights of aspects which contribute to improve the reliability of bushings during their useful life have been already collected.

It was a consensus among the WG members, that engineers should be extremely cautious when specify a particular bushing model in their procurement process. One should carefully consider if that model fits the application purpose and performance requirements while analysing all bushings and transformer features, which are confirmed by adequate type and routine tests.

1 BUSHING SELECTION TO TRANSFORMER AND REACTORS

Bushings supplied to the Brazilian market, particularly for higher voltages, are manufactured by transnational companies. Most of them have European heritage and therefore, in general, produce and test their products according to conditions of IEC standards, in this case the IEC 60137 on the latest version, which do not represent local conditions.

Bushings are components that allow the passage of current through a grounded wall. They are attached on tanks of high voltage equipment such as power transformers, shunt reactors and related.

The operational requirements of the main apparatus directly affect the operation conditions of the corresponding bushings. Local power transformers standards reflect very well those requirements, including local regulations and other local peculiarities. Bushings standards on the other hand, do not.

While transmission equipment as transformers and autotransformers are in most part customized for meet the user specifications, bushings are almost shelf products intended to be batch produced, almost no customization is economically allowed on standardized models, optimized and tested according to IEC standards.

Users with more experience tend to transform their past events of failures into more demanding requirements, aiming to prevent new occurrences. Those requirements are incorporated in technical specifications which are then used for the procurement of components, transformers and reactors. Meanwhile, there is a permanent economical pressure on engineers to reduce specifications features down to standards minimal requirements, without considering the potential future expenses due to the increased risk of fail.

1.1 Regional peculiarities

Brazil is a continental size country. Energy grid has grown at an accelerated rhythm in the past years to accommodate the growing demand for energy and currently, almost the complete electrical system is interconnected with centralized operation.

The operation of such a Continental size grid is a challenge and requires strong policies and regulations. The minimum requirements for substations and their equipments, including power transformers and shunt reactors are no exceptions [1]. For example, operational flexibility is an issue for the system operator. Therefore, an exceptional overloading cycle is desirable and therefore enforced by regulation. Figure 1 illustrates the Load Curve, with details of the minimum overload capability required to comply with local transmission regulation [1].

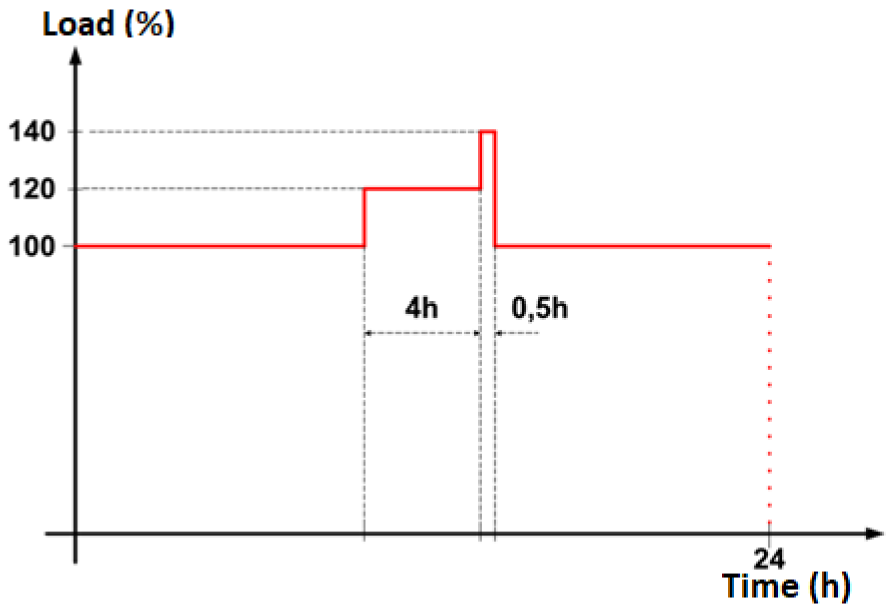

Figure 1 Daily Loading Cycle – Overload [1]

Another example refers to shunt reactors operating on the terminals of very long transmission lines across the country. In those cases, overvoltage of one hour duration is specified for the cases where the line may be held open at one end according to Table 1.

Table 1 Sustained overvoltages on line end shunt reactors [1]

Rated Operational Voltage (kV)	Maximum sustained voltage for 1 hour (phase-to-phase) at open LT	
	kV_{RMS}	**p.u.**
138	152	1,10
230	253	1,10
345	398	1,15
440	506	1,15
500	600	1,20
525	600	1,15
765	800	1,046

Most of the Brazilian territory is located between the tropics, reflecting directly on the annual mean temperature. Realistically, it can be as high as 30 °C or even more. On the other hand, maximum annual mean temperature on table 3 of IEC standard [2] is 20 °C and plainly reproduced at clause 5.3 of local bushing standard [3], unless different agreed between supplier and costumer. In this case, it is valuable to note that it is not a simple issue of changing local standard to 30 °C because price competitive bushings are not designed on demand. Alternatively, bushings according to IEEE Std. requirements could better deal with it, but with other inconvenient features.

Another feature of the Brazilian standard is the 65 K limit of the top oil temperature rise in transformers using class E materials, while IEC allows only 60 K.

2 CONSULTATION WITH EXPERTS

Once the peculiarities of national grid were collected, the task force members decided to contact all major bushings suppliers to issue questions about the impact their impact and relevance in the bushing performance.
Particularly regarding to the overload capacity for bushings, where IEC standard makes a clarification statement which is commonly employed by transformers' manufacturers almost as a rule when selecting bushings for their equipments:

> "*Bushings for transformers selected with I_R not less than 120% of rated current of the transformer are considered to be able to withstand the overload conditions according to IEC 60076-7 without further clarification or tests."[2]*.

However, nothing is mentioned about the short term peak on top of that (see Figure 1).

Therefore, considering the actual conditions of operation in the Brazilian grid It was requested the experts to provide their answers to the following questions:
1 – Would IEC criteria for thermal dimensioning "1.2 x max. transformer current" still be valid under local environmental conditions described below? Or it would be better to adjust the criteria?
2 – What may would be the impact on the bushing performance if the temperature on the oil at the top of the transformer reaches 105 °C – even for a short period of time?

Environmental and operation conditions:

- Power frequency: 60 Hz
- Oil temperature rise on the top of the transformer: +65 K

- Maximum ambient temperature: +40 °C
- Yearly average ambient temperature: +30 °C
- Load profile: according to Figure 1

2.1 Provided answers

Two experts have kindly provided their honest comments. In spite of the task force great appreciation by their contributions, their names and affiliation have been preserved confidential.

The answer provided by the first expert:

> *"The 120% "rule" in cl. 4.2 of IEC 60137 is actually only based on practical experience without need for any validation – this is indicated by the little word "considered" in the text. To further emphasize that bushings are dimensioned based on daily mean temperature the highlighted section was added to the text during the revision work preceding edition 7. … Because of the inconsistences between IEC 60137 and IEC 60076-7 the only way for the standard to actually require verification of an overload requirement would be to agree on a load cycle between the bushing- and transformer- committees of IEC and no such discussions are in progress. As already said, the 120% "rule" was a discussion item during the most recent revision work but since practical experience shows very few problems are attributed to this it was decided to just add the small clarification of which data bushings are designed from."*

Another expert answered:

> *"Your scenarios are already considered by IEC60137, IEC is the standard we strictly follow to design all our bushings.*
> *IEC Paragraph 4.2 mention that "bushing for transformer selected with I_R not less than 120% of rated current of the transformer" so overload of 1.2X is acceptable considering air and oil temperature according to Table 4.*
> *Overload 120% and oil max temperature 100°C, are scenarios accepted by IEC60137 and than by our bushing too.*
> *About the below scenario (national grid transformer overload) we kindly ask to pay attention 0,5h is not enough to reach the thermal stability, on the base of the bushing type it may rise the temperature to a very high level.*
> *We suggest in those cased of overload more than 120% to discuss case by case with bushing manufacturer. In this way the bushing maker will perform all the needed test and/or simulation to grant the acceptability of the condition."*

Regarding system power frequency, almost all IEC models of bushings are tested on laboratories whose AC power frequency is 50 Hz. Most of the time, no considerations are made with respect to frequency difference.

Skin effect has a direct impact to increase the ohmic resistance of inner conductor with the increasing of frequency. In fact, the effective cross section of conductor is reduced increasing the frequency. Considering the resistance of the bushing conductor as:

$$R = \frac{L}{2\pi * S * \delta} \qquad (1)$$

Where L is the conductor length, S is the cross-section of conductor and δ is the penetration depth of current, which for copper may be approximated to:

$$\delta_{cu} = \frac{0{,}0661}{\sqrt{f}} \qquad (2)$$

The relationship between ohmic resistance of a coper conductor at 60 Hz and 50 Hz is 1,09 higher. Thus, considering that all power dissipated on a bushing is regarding to the ohmic losses on conductor (which is a simplistic approximation), then for the same power dissipated at 50 Hz, the 60 Hz current must be approximately 4,43% lower.

For instance, to test a bushing at 50 Hz on those tests who needs to apply ac current to it, a current of 44 A each 1000 A higher must be applied to a bushing to emulate a 60 Hz condition, only considering the ohmic losses differences. Dielectric losses ($2\pi\ f\ C\ U^2\ tg\ \delta$), where the effect of frequency is direct, generally is neglected even when thermal stability test is performed at 50 Hz frequency.

For ac dielectric tests, the duration of 72 seconds instead of 60 seconds is normally attended.

3 TYPICAL SPECIFICATION'S REQUIREMENTS

As already mentioned, users tend to bring their experiences to equipment specification, each one reflecting their own criteria on their policies. Considering the impact of price of bushings compared to the transformers/ reactors' prices or even the cost of an equipment outage it is common practice to specify oversized bushings.

Due to certain distrust on bushings reliability, users generally require bushings of higher dielectric ratings than the transformer/ reactor windings. In the case of lightning impulse, a level above the windings' BIL is a typical practice. It is also not rare to find users specifying rated current for bushings that are 1.5 times greater than the current rating of the respective transformer. Perhaps, this was more common in the past, due to the lack of a load guide for bushings [4] and the user policies were not updated or maintained conservative. Others, simply apply the "rule" of 1,2 I_R to comply with the loading cycle.

External insulator requirements vary, some users require polymeric envelope (porcelain is avoided to prevent launch of pieces, shrapnel, on a major failure event). Regarding core technology restriction also varies among users. Recently, some users have been restricting the use of OIP (oil insulated paper) bushings to reduce the risk of fire in a failure event.

4.0 CONCLUSIONS

Increase the reliability of power transformer bushings implies on a relevant increase on power transformer' reliability. Therefore, the correct selection of the bushing is very important. Rationalized technical specification for procurement is user's most powerful tool to achieve this aim. However, cost pressure and newcomers with limited experience in local energy market and environment may mislead the competition toward low price and low reliability (minimal specification down to standards minimum).

The standard statement regarding overload capacity is apparently based on long term experience and lack of registered objections. It is, however, a quite critical topic due to its extensive use and the long-term impact of equipment dimensioned according to this "rule". It is also quite notable that different countries have different operation tradition and, in some places, overloading a transformer is unusual. Therefore the reduced number of objections may not be an evidence of success.

Characteristics of bushings are commonly presented at both 50/60 Hz rated frequency, even though type tests were performed at one frequency and no considerations is taken into account to extend the tests for the other frequency.

It is also necessary to have in mind that most of end users rarely buy a bushing directly from a bushing manufacturer. It is a much more common situation that the end user buys a transformer and the transformer manufacturer specify it from the bushing manufacturer. Therefore, users may state clear requirements in the transformer specification if they need to increase bushing reliability in the procurement process.

The results will be submitted to National Standard Committee, at this time reviewing the Bushing Standard, to feed discussions of bushings requirements, especially on overload requirements.

BIBLIOGRAPHY

[1] Submódulo 2.6 – Requisitos mínimos para subestações e seus Equipamentos (Operador Nacional do Sistema Elétrico – ONS) Rev. 2021.08 http://apps08.ons.org.br/ONS.Sintegre.Proxy/ecmprsite/ecmfragmentsdocuments/Subm%C3%B3dulo%202.6-RQ_2021.08.docx_16c3ed7c-cf3b-4cf6-aca5-9bfdabe244af.pdf

[2] IEC 60137 – Insulated bushings for alternating voltages above 1 000 V. Ed. 7.0 jun 2017.

[3] ABNT NBR 5034 – Buchas para tensões alternadas superiores a 1 kV. Segunda edição 2014.

[4] BOSSI, A., YAKOV, S. Bushings and connections for large power Transformers. Cigre Bienal Paris, SC 12, 1984.