New burden definitions for voltage and capacitor voltage transformers

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***Abstract*—Accuracy requirements for voltage transformers and associated standard burdens were defined decades ago. Since then, the devices that connect to the secondary terminals of instrument transformers have evolved drastically. The aim of this paper is to provide context and background of why existing burdens are no longer optimal for modern power systems. In line with that, new standard burdens are proposed. The reasons and justification of their selection are explained in detail. This paper provides a broader information set than is typically provided in international standards because standards typically limit the amount of explanatory text. Lastly, this paper describes and verifies a calculation method applicable for accuracy performance assessment with a level of error that corresponds to laboratory-grade measurements.**

Keywords— Voltage transformers, accuracy performance, standard accuracy burdens,

I. Introduction

Accuracy performance is the key functional aspect of every instrument transformer. Instrument transformers are used to step down the desired electrical quantity, current or voltage depending on the instrument transformer type, to a measurable value. In doing so, the transformation of that quantity must remain very accurate to ensure precise energy billing and reliable fault detection, enabling correct operation and timely tripping of circuit breakers. To define what accurate means, the concept of accuracy classes and associated burdens was introduced decades ago [1]. That concept has remained relatively unchanged over time and is still present in the instrument transformer standards [2], [3].

However, the devices that connect to the secondary terminals have changed dramatically, evolving from analogue meters and mechanical relays to electronic meters and relays. This evolution has not been accompanied by corresponding updates to existing accuracy classes and burden specifications.

The accuracy limits concept is devised around the transformer correction factor (TCF) which considers both the ratio correction factor (RCF) and the phase angle (γ). TCF shows the overall effect on watthour meter registration with the idea that the TCF has to remain within specified certainty limits, known as accuracy classes. The basic relationship between TCF, RCF and γ is shown in equation (1), while the standard accuracy limits are shown in Fig. 1.

Voltage transformers must be within those accuracy limits for the specified standard burden range. The existing burden definitions are based on analogue devices which are no longer in widespread use and are found only in legacy applications. This is specifically apparent with inductive voltage transformers (IVTs), coupling capacitor voltage transformers (CCVTs) and voltage active parts of combined units [4], [5], [6]. The existing standard burdens are shown in Table I [2],[3].

The upcoming revision of the IEEE C57.13 standard will introduce new standard burdens to narrow the gap between existing burden definitions and actual installations in modern systems [5]. The majority of work is conducted within the Instrument Transformer Accuracy Taskforce within the IEEE PES Transformer Committee. This paper outlines the main accuracy concepts and how they influence transformer design. Furthermore, the paper presents an updated proposal for standard burdens that adequately reflect the modern meters and relays. It also details accuracy calculations that can support laboratory-measured data in order to precisely determine the accuracy performance at different burdens and power factors. The context this paper provides is of value to users, manufacturers and third parties. The scope of this paper applies to all conventional voltage transformer types regardless of the voltage level, geometry or insulation system.

$$TCF = RCF + \frac{\gamma}{2600} \tag{1}$$

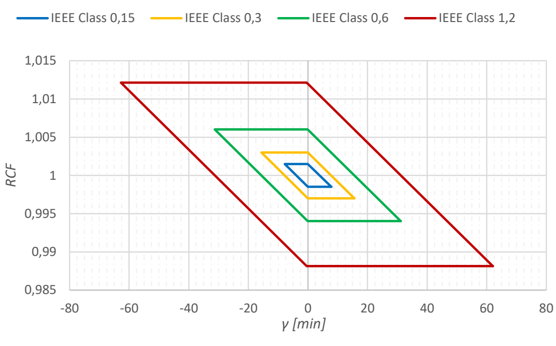

Fig. 1 Accuracy class limits for voltage transformers

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TABLE I STANDARD BURDENS FORM EXISTING STANDARDS [2], [3]

Designation	Load [VA]	Power factor
W	12.5	0.1
X	25.0	0.7
M	35.0	0.2
Y	75.0	0.85
Z	200.0	0.85
ZZ	400.0	0.85

II. BASIC ACCURACY CONSIDERATIONS

The basic inductive voltage transformer equivalent diagram is shown in Fig. 2 [7], [8]. To simplify the representation, a transformer with two windings is shown. The equivalent diagram for CCVTs is more complex, but the main concepts shown here apply to CCVTs as well. This diagram will be used to illustrate several scenarios in this section.

The first concept is voltage ratio error (defined as RCF) and phase error. Assuming an unloaded transformer (Z_{21} and Z_{22} equal to 0 VA), there is no load current flowing through the transformer windings, meaning that currents I_{21} and I_{22} are equal to 0 A and current I_1 is equal to the magnetizing current I_0 necessary to magnetize the transformer core. This current causes voltage drops on equivalent elements R''_1 (primary winding resistance) and X''_1 (leakage impedance) which manifest as voltage error and phase shift. These errors are typically very small as the magnetizing current is substantially smaller than the load current when the burden is applied. This scenario is considered the first obligatory point of accuracy performance which is routinely tested on every transformer. In layman's terms, the accuracy is tested at 0 VA (unloaded transformer). It should be noted that even if the transformer is unloaded during the test, a small burden is present due to measurement bridges and other equipment.

The second scenario is when one winding is loaded with its rated standard burden. An example of an inductive voltage transformer with accuracy class 0.3 and Z burden from Table I are used to illustrate the point. In this case, impedance Z_{21} corresponds to the Z burden. The nominal load current I_{21} is now present in the secondary winding elements R_{21} and X_{21}. Load current I_1 is now a vectorial sum of load current and magnetizing current I_0. This current causes voltage drops on R''_1 and X''_1 elements. The vectorial voltage drops across the internal impedances manifest as both voltage and phase errors. This scenario is the second obligatory point of accuracy testing. Both scenarios are shown in Fig. 3 a).

The third scenario is the so-called simultaneous loading. For units that have more than one secondary winding, both windings can be loaded at the same time. All secondary windings share the same magnetic core, so they influence each other through voltage drops on R''_1 and X''_1 elements. Burden definitions in [2] and [3] dictate that the maximal standard burden from Table I can be distributed between multiple windings in any manner (e.g. 100 VA on winding 1 and 100 VA on winding 2). In this case the errors of each winding are smaller than if the full load is applied to a single winding. This is because the voltage drops on secondary elements (i.e. R_{21}, X_{21} and R_{22}, X_{22} respectively) will be smaller in comparison. This is also illustrated in Fig. 3 a).

The last effect considered is if the windings are loaded with their thermal burden, which is defined as the largest burden for which the unit stays in its temperature rise class. A typical thermal burden is several times higher than maximal standard burdens (e.g. 1000 VA, 2000 VA, 4000 VA or even higher). When a thermal burden is applied, the accuracy performance is no longer required to be guaranteed [2], [3]. Some users still perceive that they can use one winding for metering and relaying purposes and the other for small power supply. This may be physically possible, but the metering winding, due to the simultaneous loading effect will be driven out of accuracy [8]. This is shown in Fig. 3 b).

Even though thermal burden is not directly connected to the accuracy burdens, the same physical properties influence both. While larger standard burdens (e.g. Z or ZZ) do inherently mean a higher thermal capability, the actual usability of the unit is still limited by the metering accuracy [4]. This is why the thermal capability of the metering-grade transformers should be kept only to emergency situations and temporary operation. For continuous power supply the unit should be designed accordingly, or SSVTs should be used [8].

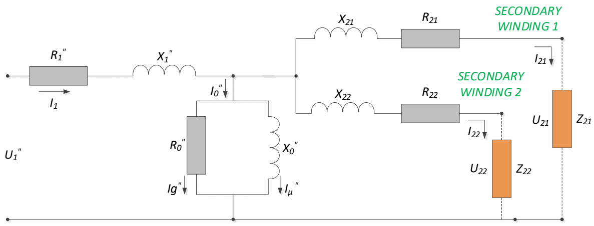

Fig. 2 Equivalent diagram of the voltage transformer

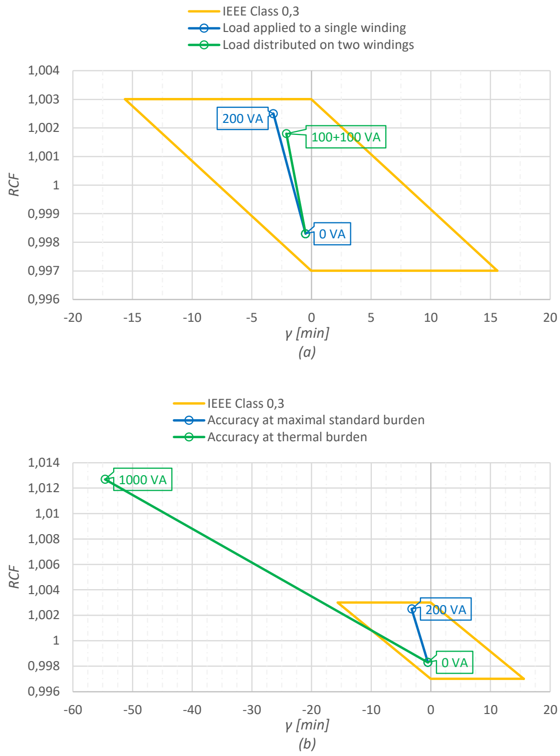

Fig. 3 a) Accuracy performance with load on a single winding in comparison to evenly distributed among two windings b) Comparison of accuracy performance at thermal burden and maximal standard burden

III. PERFORMANCE ASPECTS OF EXISTING BURDENS

As mentioned in the introductory sections of the paper, existing burdens, shown in Table I, were devised long before the era of digital meters and numerical relays [1]. A typical burden of legacy metering and relaying apparatus was in tens or even hundred voltamperes, while a typical burden of

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modern meters and relays is around several VA or even below 1 VA in some cases. In addition, the power factor of digital equipment is close or equal to unity. These two effects have several influences on transformer accuracy performance, which are detailed below.

The first effect is best seen in W, X and M burdens which have a rated power factor significantly lower power factor than what is realistically found in operation. Depending on the total value of the applied realistic burden they may no longer be in the designated accuracy class. This is exemplified by measurement data acquired on a medium voltage 7.2 kV VT with M accuracy class. The data is shown in Fig. 4a). This means that even though the unit was properly tested in accordance with the standard, it still does not satisfy the accuracy performance in the field.

The second effect is more prominent with higher burdens (i.e. Y, Z and ZZ). To keep the design of the transformer optimal, typically the full range of standard allowed accuracy limits is used. As explained in the last section, any reduction in transformer errors necessitates an increase in its geometry, or the geometry of some internal components. The innate approach many customers use is to specify the largest burdens (e.g. Z or ZZ) to have ample margin. However, this approach is not optimal in this scenario, as that consequently entails operation at the very limit of accuracy, as exemplified in Fig. 4 b). In this case, if the actual burden power factor deviates from the standard burden with which the unit is tested, the accuracy can stray outside the accuracy limits, even for fairly low values of burden. This is because the majority of the accuracy limit parallelogram area is "reserved" for accuracy performance that is seldom encountered in the field. This means that the customers are essentially paying more to receive worse accuracy performance. An example of such case is measured data on a 245 kV VT, shown in Fig. 4b).

Both of these examples emphasize the point that the existing burdens are not optimally defined. In addition, an array of standard burdens with different power factors makes testing more complicated, as the physical burdens have to include varying resistive and inductive components.

IV. Proposal for New Standard Burdens

Multiple sources of data, similar to the ones shown in the previous section, obtained from different manufacturers were the basis for the proposal of new standard burdens for voltage transformers.

To rectify the issues with the existing burdens, two proposals are introduced:

- The standard burdens are now defined exclusively with a unity power factor
- The standard values of burdens are reduced (both in the number of variations and their values)

The first proposal was done for two reasons. The first is to simplify testing. The second is to assure with a higher degree of certainty that the unit will be in accuracy class for realistic burdens regardless of the power factor. The data shown in Fig. 4 a) and b) clearly show that the unit will stray out of accuracy at the lowest burden if the burden power factor is equal to unity. Fig. 4 c) shows an example where the same unit from Fig. 4 b) was reworked to be in accuracy class for Z burden with a unity power factor. As it can be seen, the burden values where the unit is outside of accuracy are significantly higher.

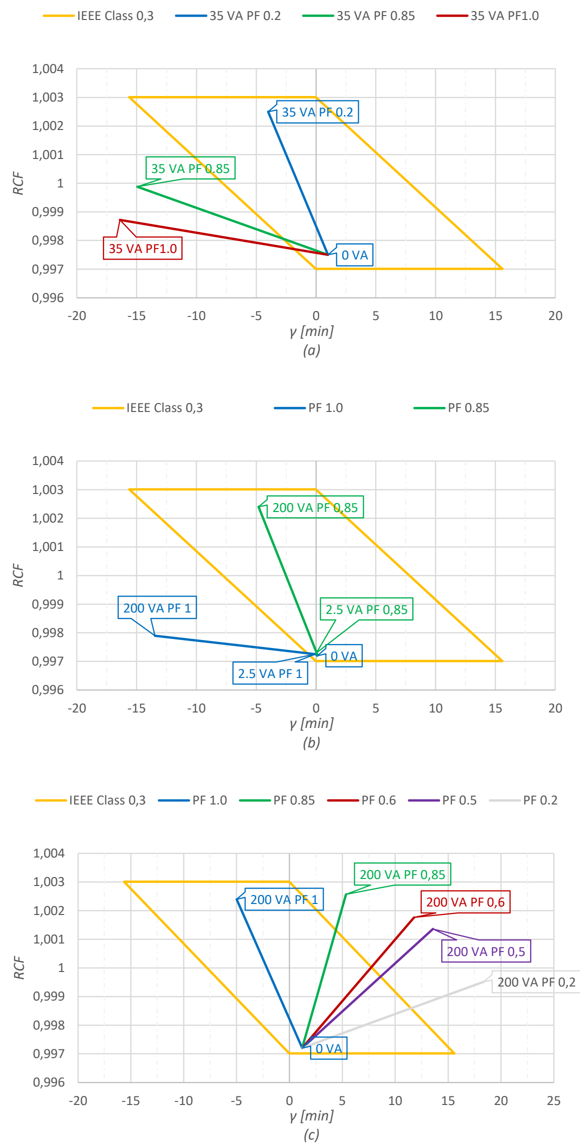

Fig. 4 a) Accuracy performance of Class 0.3M 7.2 kV VT with realistic power factors b) Accuracy performance of Class 0.3Z 245 kV VT with realistic burden and power factors c) Accuracy performance of Class 0.3Z 245 kV VT optimized to be in accuracy for unity power factor

The second proposal was done to reflect the actual typical on modern burdens. The reduction in the absolute burden value allows for better accuracy performance of existing designs or a possible reduction in the overall transformer geometry, or potentially both.

The new standard burdens as proposed by the Instrument Transformer Accuracy Task Force, and implemented in the latest IEEE C57.13 draft are shown in Table II [5]. The letter designations were selected not to interfere with other commonly used letter designations in the industry. Burden J is selected for low power, single winding applications, while burdens K and N are tailored towards two or three winding configurations.

TABLE II New Standard Burdens

Designation	Load [VA]	Power factor
J	2.5	1.0
K	25.0	1.0
N	75.0	1.0

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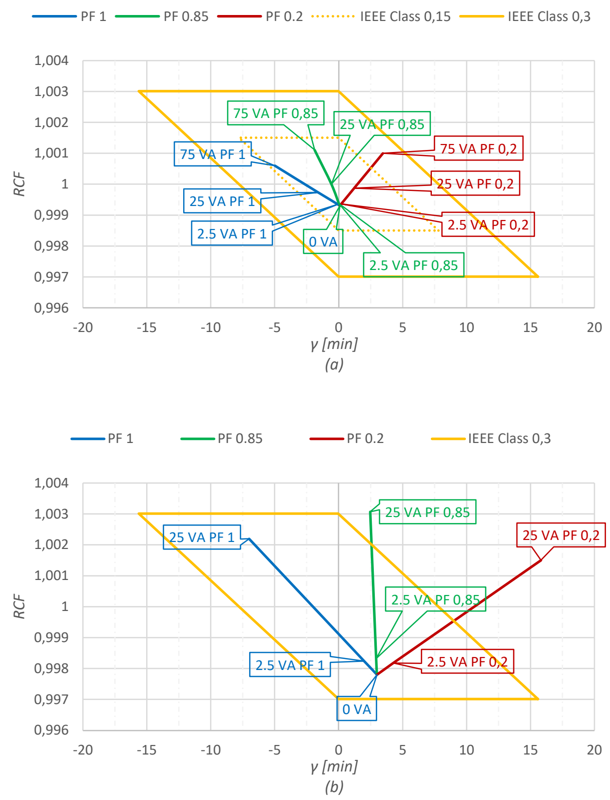

Fig. 5 a) Accuracy perfromance of Class 0.3Z 245 kV VT optimized to be in accuracy for new standard burdens J, K and N. b) Accuracy perfromance of Class 0.3K 245 kV VT with reduced geometry

Example of the same overall VT design from Fig. 4 optimized for the new burdens is shown in Fig. 5 a). In this case optimization only means corrections of the turn number, not of the transformer geometry. The measurements were done at three power factors (unity, 0.85 and 0.2) to demonstrate the behavior even if the load power factor is further away from typical values.

As can be seen, the design is well within the limits of accuracy class 0.3 for each of the new burdens. Furthermore, this specific unit is also within the limits for accuracy class 0.15, for all burdens and power factors with the exception of 75 VA at power factor of 0.2. The previous burden definitions would prevent that as the zero point of the burden range would be close to the limit of 0.3 accuracy and outside the 0.15 accuracy limit parallelogram, as shown in Fig. 4.

Fig. 5 b) shows an example of accuracy performance of a unit optimized for the new burden designation K. In this case optimization assumes a change (reduction) in transformer geometry. It can be seen that the unit does stray outside of accuracy at the top of the burden range for power factors 0.85 and 0.2. However, the difference in comparison to the existing legacy burdens is that the range of power factors with a highest market relevance (i.e. unity or close to unity) has a higher degree of probability to be within the accuracy class limits, even with a reduced geometry.

It is important to note that, as discussed in Section II, a lower burden range may entail a reduction in the overall thermal capability of the unit. This is design-specific, but still worth mentioning.

To ensure backward compatibility with decades of experience in the industry, and to allow for new applications where higher burdens are needed, the existing burdens shown in Table I are kept in the standard, but moved to a separate section [5].

V. Calculations Related to Voltage Transformer Performance

In addition to the new burden definition that increases the probability for units to be within its designated accuracy limits for realistic burdens with realistic power factors, the new standard advocates the use of simple calculation methods that are design independent and can be used by customers, manufacturers and third parties [5]. The methodology is described in detail in the standard itself, so it will be presented in this paper in its abbreviated form.

The necessary input for the calculation method are:

- Measured data (RCF_l and γ_l) when the transformer is unloaded or at a low burden value B_l
- Measured data (RCF_t and γ_t) when the transformer is loaded with its maximal standard burden B_t

Both input points need to be obtained at the same power factor, same frequency, same winding and same voltage (e.g. 100% of the performance reference voltage). Alternatively, the first data point can be obtained from a lower standard burden with the same power factor (e.g. burden J for the first data point and burden K for the second data point). Furthermore, even a measurement on an unloaded transformer has a certain burden associated with it, specifically the burden of the measurement bridge, or other measurement equipment. This is why it is highly recommended to use the method to calculate the transformer errors at true zero (RCF_0 and γ_0).

The method consists of two steps:

- Calculation of accuracy (RCF_0 and γ_0) at true zero burden from measured data points using equations 2) and 3)
- Calculation of accuracy (RCF_c and γ_c) at other burdens B_c and power factors using equations 4) and 5)

$$RCF_0 = RCF_t + \left(\frac{B_t}{B_t - B_l}\right) \times (RCF_l - RCF_t) \tag{2}$$

$$\gamma_0 = \gamma_l + \left(\frac{B_l}{B_t - B_l}\right) \times (\gamma_t - \gamma_l) \tag{3}$$

$$RCF_c = RCF_0 + \left(\frac{B_c}{B_t}\right) \times \\ \times [RCF_d \times cos(\theta_t - \theta_c) + \gamma_d \times sin(\theta_t - \theta_c)] \tag{4}$$

$$\gamma_c = \gamma_0 + \left(\frac{B_c}{B_t}\right) \times \\ \times [\gamma_d \times cos(\theta_t - \theta_c) - RCF_d \times sin(\theta_t - \theta_c)] \tag{5}$$

In equations 4 and 5 θ_t and θ_c are the power factor angles of the measured input data (burdens B_t and B_l) and of the desired burden calculation point (B_c), expressed in radians. RCF_d is expressed as $RCF_t - RCF_0$ and γ_d is equal to $\gamma_t - \gamma_0$.

The accuracy of this approach was showcased on different design types, ranging from low-voltage units to high-voltage instrument transformers with different geometries and insulation systems [5]. To illustrate the accuracy of the method for this paper a numerical analysis of the example shown in Fig. 4 are used, as it contains the most measured points to validate the method. Even though any pair of points sharing the same power factor can be used, for the sake of simplicity 2.5 VA and 200 VA, both with a power factor of 0.85 were used as input data. A detailed comparison of calculated and measured values is given in Table III.

The average error of the example demonstrated in Table III is 0.006% for RCF and 0.068% for γ. The maximal errors are 0.048% for RCF and 0.168% for γ, respectively. This clearly demonstrates the applicability of the method. The strength of the method is that it is easily implemented into different software solutions, it is geometry independent and equally as applicable for VTs, CCVTs and combined units of different voltage levels, insulation systems and structural features. The main benefit of the method is the very easy construction of accuracy plots for any burden and burden power factor from two measurement points. An example of such accuracy plot is shown in Fig. 6.

In order to standardize the input data, the new standard will mandate accuracy measurement of the unloaded transformer and at the maximal rated burden (J, K or N) [5].

It needs to be stated that this method can be used to extrapolate beyond the maximal rated burden (e.g. to 400 VA from a measured value of 200 VA). However, in this case larger errors can be exhibited. Therefore, extrapolation beyond the maximal rated burden shall be used for indicative purposes only. Additionally, for small burdens (e.g. J burden), it is necessary to specify the bridge and instrumentation burden for the measurement of the unloaded transformer and extrapolate back to true zero burden.

VI. Conclusions

The aim of this paper is to provide a broader context for the selection of new standard burdens that will be recommended in the new revision of the IEEE C57.13 standard [5].

There are three main drawbacks of the existing burdens:

- They no longer represent the actual burdens of modern meters and relays in the field
- Even if the unit is within the limits for the accuracy class and the respective power factor, it still may be outside of accuracy at a realistic power factor, even at low burden values
- Units that have a high burden specified realistically operate close to the accuracy limit and use the available accuracy parallelogram area poorly

The newly proposed burdens rectify those issues by:

- Specifying more realistic burden values and power factors
- Requiring the accuracy performance at burdens with unity power factor which increases the probability that the units will be in accuracy for other power factors
- Simplifying testing procedures

Table III Comparison of measured and calculated accuracy performance for 245 kV VT

Burden	Measured values		Calcualted values		Δ RCF [%]	Δ γ [%]
	RCF	γ [min]	RCF	γ [min]		
2.5 VA, PF 0.85	0,9973	1,25	-	-	-	-
200 VA, PF 0.85	1,0026	5,34	-	-	-	-
0 VA	0,9972	1,20	0,9972	1,20	2,31E-04	0,17
2.5 VA PF 1.0	0,9973	1,12	0,9973	1,13	2,91E-04	0,07
200 VA PF 1.0	1,0024	-5.00	1,0024	-5,01	9,98E-05	0,14
200 VA PF 0.6	1,0018	11,78	1,0018	11,77	2,99E-04	0,08
200 VA PF 0.5	1,0014	13,58	1,0014	13,57	2,00E-04	0,07
200 VA PF 0.2	0,9995	17,76	1,0000	17,76	4,86E-02	0,02

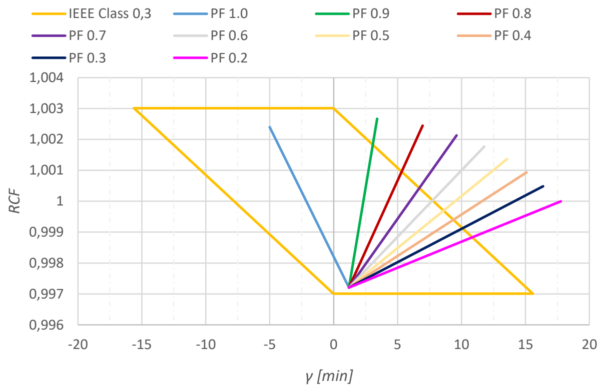

Fig. 6 Accuracy fan plot for 245 kV VT obtained through calculation

In addition, new burden definitions are supported by a demonstrated calculation method that is able to provide laboratory-grade accuracy for any burden and power factor, as long as it is lower than the maximal standard burden specified.

All the changes introduced and detailed in this paper are necessary to ensure the adequacy of the main instrument transformer functionality for decades to come.

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