An innovative approach: Agile methodologies for the design of power circuit breakers

https://doi.org/10.56238/sevened2024.004-005

Paulo Roberto Duailibe Monteiro[1], Thiago Trezza Borges[2] and André Fernando Schiochet[3]

ABSTRACT
During the increasing complexity of electrical systems, the need for more effective and accessible methods becomes evident, seeking to balance technical precision, operational practicality and safety. This article proposes an innovative and simplified method for the sizing of power circuit breakers, aiming to optimize the efficiency of the selection process of these crucial equipment for the electrical infrastructure. The sizing methodology aimed at specifying the main characteristics of power circuit breakers offers a systematic and comprehensive approach, integrating critical considerations ensuring the correct functioning of these equipment in various electrical contexts. The process consists of several steps, covering everything from the initial analysis to the final selection of the appropriate circuit breaker. The modified power method is applied to the definition of the short-circuit characteristics and is introduced in the sizing criteria based on the operation of the electrical system for the analysis in normal operation of the system. A test system of a pumping station consisting of a 69 kV substation is studied. The proposed methodology met its objectives, presenting precision and effectiveness, and can be a very useful tool for project engineers in electricity.

Keywords: Short circuit, Power flow, Power circuit breakers, Circuit breaker sizing, Specification of circuit breakers.

[1] Doctor
Dr. in Civil Engineering
Fluminense Federal University (UFF), Niteroi, RJ, Brazil
E-mail: pauloduailibe@id.uff.br
ORCID: https://orcid.org/0000-0002-7376-9115
[2] Doctor
Dr. in Electrical Engineering
Fluminense Federal University (UFF), Niteroi, RJ, Brazil
E-mail: thiagotrezza@id.uff.br
ORCID: https://orcid.org/0000-0003-4656-5667
[3] MSc
MSc in Electrical Engineering
Brazilian Petroleum Company (Petrobras), Rio de Janeiro, Brazil;
E-mail: eel.afs@gmail.com
ORCID: https://orcid.org/0009-0005-2062-1984

INTRODUCTION

In the electrical engineering scenario, power circuit breakers play a crucial role in maneuvering, protecting, and controlling electrical power systems (SEE). High-voltage circuit breakers represent a fundamental piece in the global electrical infrastructure, ensuring the reliability and security of power supply in various industrial and commercial applications.

In electrical systems, circuit breakers are required to perform the basic function of controlling the electrical power transmitted by them, either by conducting the load current of the circuits, or by maneuvering the closure of circuits or even the withdrawal of services from circuits under nominal or automatic command. Circuit breakers normally operate in the closed position, conducting the load current, or in the open position in which they operate by exerting insulation. Only in occasional situations are circuit breakers triggered to change position, i.e. to change from open to closed or from closed to open, and only on rare occasions are they triggered to interrupt short-circuit currents [1].

This equipment is designed to interrupt short-circuit currents in very short intervals of time, representing one of the most challenging tasks entrusted to the equipment present in power systems. They must also be able to establish fault currents, to establish and interrupt currents of much smaller magnitudes, and to isolate parts of systems when in the open position. The execution of these tasks, in an absolutely reliable manner, is imperative to prevent damage to other components of the electrical system, positioning the circuit breakers among the most complex equipment installed in the substations [2].

The challenges associated with circuit breakers are multifaceted, ranging from the ability to interrupt short-circuit currents at minimal intervals to the need to operate under harsh environmental conditions for prolonged periods [3]. The complexity of these demands places circuit breakers among the most intricate and critical pieces of equipment in electrical power system (SEP) substations.

Thus, the requirement imposed on power circuit breakers is that of total reliability, and this reliability is the result of a rational design and strict quality control. This process ranges from the careful selection of raw materials to the final stage of the tests, encompassing the input review, materials testing, thorough control of the manufacturing processes, tests on sub-assemblies and, finally, the final tests. Commitment to each phase of this development cycle is vital to ensure not only compliance with technical specifications, but also the durability and operational efficiency required in challenging environments. This integrated and comprehensive approach reflects the relentless pursuit of excellence in power circuit breaker engineering, grounded in sound practices and uncompromising pursuit of quality.

In this context, the precise and efficient performance of circuit breakers plays a strategic role in the stability and safe operation of electrical systems. Their ability to transition between states, from drive to disruption, reflects not only the complexity of their responsibilities, but also the need to solidly balance operational reliability with efficiency. This scenario serves as a backdrop to the critical importance of innovative advancements and in the sizing and application of these devices.

This paper proposes an innovative approach in the sizing of high-voltage circuit breakers, presenting a simplified method that aims to optimize the selection process of these devices. Understanding and applying sizing procedures is essential to ensure that circuit breakers meet the specific requirements of each electrical system, balancing effectiveness, cost, and efficiency.

The areas of knowledge for the training of electrical engineering professionals include the study of electrical equipment, including circuit breakers. The need to know electrical equipment and experience its actual operation is fundamental [4]. Streamlining the sizing process not only streamlines decision-making but also promotes a more accessible and faster understanding for professionals in the field. This study aims to contribute significantly to the operational efficiency and continuous development of electrical systems, by offering an innovative methodology for the sizing of high voltage circuit breakers.

In the following sections, the fundamentals of circuit breaker sizing are explored, highlighting the importance of considering critical variables such as system load, short-circuit characteristics, and coordination requirements. Next, the proposed simplified method is presented, detailing its premises, applicability and advantages compared to traditional approaches.

FEATURES FOR SPECIFICATION AND DEFINITIONS

Power circuit breakers are the main safety equipment, as well as the most efficient switchgear in use in electrical networks. They have a closing and rupture capability that must meet all established maneuvering prerequisites, under all normal and abnormal operating conditions [5]. IEC 56-1 apud [3], defines a circuit breaker as "a mechanical switching device, capable of establishing, conducting, and interrupting currents under normal circuit conditions, as well as establishing, conducting for a specified time, and interrupting currents under specified abnormal circuit conditions, such as short-circuit conditions."

The main function assigned to circuit breakers is to interrupt fault currents as quickly as possible, in order to minimize the potential damage caused to equipment by short circuits. In addition to dealing with fault currents, it is imperative that the circuit breaker be able to interrupt normal load currents, magnetizing currents coming from transformers and reactors, as well as capacitive currents associated with capacitor banks and no-load lines [2].

Additionally, the circuit breaker must possess the ability to close electrical circuits not only during normal load conditions, but also in the presence of short circuits. The most common functions performed by circuit breakers include, firstly, the conduction of load currents when in the closed position, followed by the function of isolation between two parts of an electrical system [2].

With respect to this function, the circuit breaker being in the open or off state, the insulation distance between the contacts must be able to withstand not only the operating voltage, but also the internal overvoltages arising from maneuvering surges or lightning strikes.

The main characteristics applicable to circuit breakers are listed below, as well as the corresponding definitions, as shown in [5].

- Rated Voltage: It is the maximum operating voltage of the system for which the circuit breaker was provided;
- Rated current: It is the effective value of the continuous regime current that the circuit breaker must be able to conduct indefinitely, without the temperature rise of its different parts exceeding the specified values;
- Rated frequency: It is the system frequency for which the circuit breaker will operate;
- Rated short-circuit interrupting capacity: This is the highest value of the short-circuit current that the circuit breaker is capable of interrupting, under the conditions of use and testing established in the IEC 62271-100 standard. It is characterized by the declaration of the values of the periodic and aperiodic components of the current for which the circuit breaker is to be tested [2];
  - Periodic component value (kA, effective): It is a value chosen among the several defined in the technical standards, higher than the effective value of the highest single-phase or three-phase short-circuit current calculated for the substation where the circuit breaker will be installed;
  - Value of the aperiodic component: The DC component of the fault current, at the time of separation of the circuit breaker contacts, is specified as a percentage of the initial ICCO value, where ICCO = ICA(peak). The percentage value will express the %ICCO / ICA(peak) ratio × 100. The shortest possible opening time for the definition of this component will consider a protection actuation time of 0.5 cycles. Thus, the value of the CC component varies, over time, according to the exponential (1):

$$I_{CC}(\%) = e^{\frac{-t}{\tau}} \times 100 \quad (1)$$

Let the time constant conform to (2):τ

$$\tau = \frac{1}{\omega} \cdot \frac{X}{R} \cdot 1000\ (ms) \quad (2)$$

- Nominal short-circuit setting capacity (kA, crest): It is the highest instantaneous value of current that the circuit breaker is capable of establishing, i.e., close and latch when operating at rated voltage. Its value can be calculated by (3):

$$I_{fmax} = I_{CA\,ef} \times f \qquad (3)$$

Where f is the asymmetry factor, defined as (4):

$$f = \sqrt{2} \cdot (1 + e^{\frac{-t}{\tau}}) \qquad (4)$$

The peak value is linked to the rms value of the rated short-circuit interrupting current, frequency, and time constant (τ). The values specified according to [6] are:

- 2.5 x short-term withstand current rated at 50 Hz at τ = 45 ms
- 2.6 x short-duration rated withstand current at 60 Hz at τ = 45 ms
- 2.7 x rated short-duration withstand current at 50/60 Hz at τ > 45 ms (*)

(*) For all special time constant cases

- Rated Insulation Level: Defines the withstand values of the voltages and overvoltages for which the circuit breaker is designed. It should be chosen from the values indicated in the reference tables [7].
- Nominal Sequence of Operation:

The nominal sequences of operations standardized by ABNT are as follows:

- For circuit breakers intended for rapid reclose:

O-0.3s-CO-15s-CO or O-0.3s-CO-3min-CO

- For circuit breakers not intended for fast reclose:

CO-15s-CO or O-3min-CO-3min-CO

- Rated Interrupt Time:

It corresponds to the longest time that the circuit breaker can take to interrupt a current of any value. This time ranges from 2 to 5 cycles. According to [5], it is recommended to adopt the following interrupting times in the circuit breaker specifications according to the voltage class:

- Voltage class 362, 460, 550 and 800 kV: 2 cycles;
- Voltage class 72.5, 145 and 245 kV: 3 cycles;

- Voltage class 15 kV: 5 cycles.

- Disjunctor Type

A guideline for selecting the type of circuit breakers according to the voltage class presented in [5] is described below:

- Voltage class: 5kV to 38 kV

Vacuum or SF6 circuit breakers. Being the preferred vacuum, although there is a relative equivalence between them, they are competitive.

- Voltage class: 72.5kV to 245 kV

SF6 circuit breakers

- Voltage class: ≥ 365 kV

Compressed air and SF6. SF6 being preferred in most cases.

SIZING METHODOLOGY

Knowing how to size equipment is critical for every electrical engineer, especially for equipment engineers, however, to size them may not be an easy task. The sizing methodology aimed at specifying the main characteristics of power circuit breakers must necessarily offer a systematic and comprehensive approach, integrating critical considerations to ensure the correct functioning of this equipment in various electrical contexts. The process consists of several steps, covering everything from the initial analysis to the final selection of the appropriate circuit breaker. Table 1 shows the main phases of the circuit breaker selection methodology.

Table 1: Methodological phases of the design and selection process.

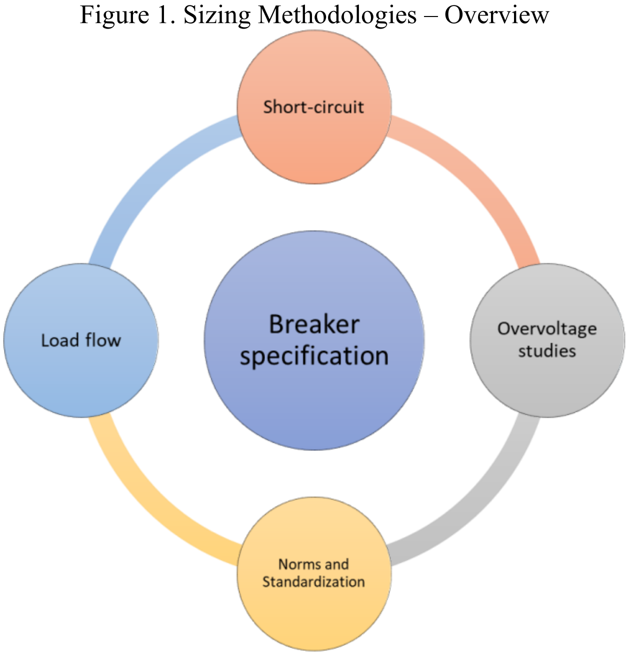
Phases of the Process	Objective
1-Electrical System Analysis	Evaluation of electrical system configuration and characteristics, including load, short circuit, and coordination requirements.
2- Identification of Parameters	Survey and identification of critical parameters such as rated current, short-circuit current, operating characteristics, and other system-specific factors.
3- Power Flow Analysis	Performing analysis to determine the ability of the circuit breaker to handle the predicted load currents, ensuring that the temperature rise is within the specified limits
4- Short Circuit Analysis	Evaluation of the circuit breaker's ability to withstand and interrupt short-circuit currents, taking into account interrupt times, short-circuit levels, etc.
5- Circuit Breaker Type Selection	Appropriate choice of circuit breaker types, considering the specific characteristics of the system and environmental conditions
6- Documentation and Report	Preparation of detailed documentation, including technical specifications, calculations, and justifications for the final selection of the circuit breaker.

Within the methodological process presented, electrical studies stand out as of fundamental importance. Basically, the studies necessary for the specification of the electrical characteristics of the circuit breakers are: study of power flow for the determination of the nominal current; short-circuit study to determine short-circuit withstanding and interrupting capacity; study of overvoltages to determine insulation levels and TRT (Transient Restoration Voltage) [8].

To carry out these studies, computational resources are usually used. Computer programs play a key role by providing powerful tools for analyzing complex electrical systems. There are a number of widely recognized platforms for analysis and simulation of electric power systems that include advanced tools and robust capabilities for power flow and short-circuit calculations, as well as stability studies and grid planning.

In view of the above, the challenge is to design and specify power circuit breakers without computational resources. Thus, the proposed methodology for the design of circuit breakers aims to offer a systematic and comprehensive, but simplified approach of direct and objective application, considering premises that allow shortcuts in the execution of calculations. Figure 1 shows the general outlines of the sizing methodologies.

Figure 1. Sizing Methodologies – Overview



Conventional methods for short-circuit calculation involve many formulas, increasing complexity and requiring a lot of time. As demonstrated in [9], the power method has been shown to be quite simple and effective in terms of speed, accuracy, and economy to solve short-circuit problems in industrial electrical systems. Thus, the proposed methodology for the sizing of circuit breakers is based on the modified power method for the calculation of short circuit. The equations used in the short-circuit calculation are as follows [5] and are presented below.

$$Scc conc = \sqrt{3}\ .\ kVnominal\ .\ Icc_{Conc}\ .\ 10^{-3} \quad (5)$$

$$X_{th} = \frac{S_b}{S_{cc}} \quad \text{(PU)} \tag{7}$$

$$X_{pu} = X_{pu}\frac{S_b}{S_{Equip}} \quad \text{(PU)} \tag{8}$$

$$S_{k(3)} = \frac{S_b}{X_{pu}} \quad \text{(MVA)} \tag{9}$$

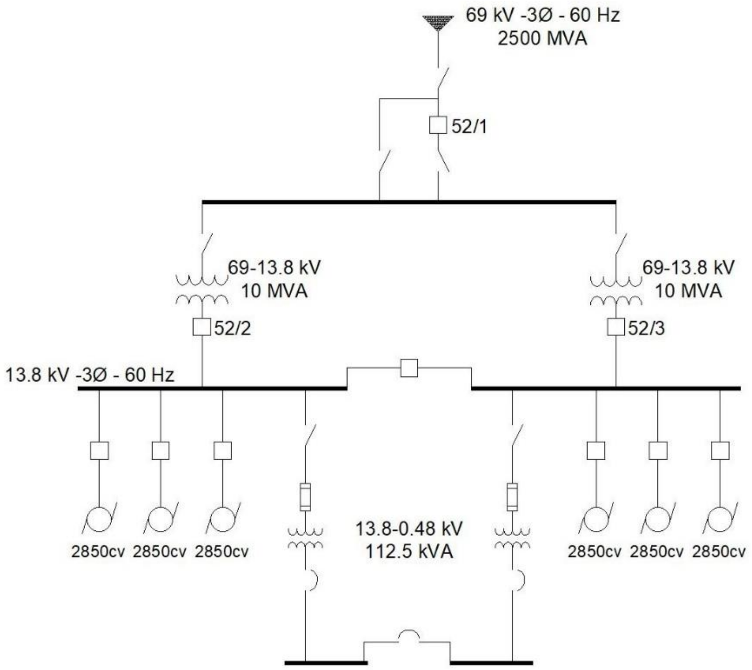
$$I_{k(3)} = \frac{S_{k(3)}}{\sqrt{3}\ V} \quad \text{(kA)} \tag{10}$$

Regarding the definition of the nominal current of the circuit breaker, it must be considered that it has to be higher than the maximum current that circulates in the section where the circuit breaker will be installed. Normally, the currents that circulate in the stretches are obtained through the study of the power flow with the help of computers. However, the definition of the maximum current that can circulate in a given section of the electrical system for equipment sizing must comply with sizing criteria based on the operation of the system, such as contingency, release flow of the full capacity of the transformers, in the case of the branch under its control, among others.

TEST SYSTEM

The electrical system of a water pumping station consists of a 69 kV substation (SE) with radial and selective secondary arrangement containing two 10 MVA transformers that lowers the voltage to 13.8 kV to power six sets of 1850 hp motor pumps. Two 112.5 kVA transformers are connected to the 13.8 kV bus, as shown in the single-line diagram shown in Figure 2.

Figure 2. Simplified one-line diagram



The short-circuit power considered at the entrance of the substation to the project horizon was 2500 MVA. An impedance of 6% was considered for the 10 MVA (TF) power transformers. The motors (M) are induction, three-phase with an efficiency of 95%, a power factor of 85% and a subtransient impedance of 17%. The impedance of auxiliary services transformers (TSA) was considered to be 4.5%. The system has no operational restriction, being able to operate both in "L" and "H", that is, it is allowed to operate the transformers in parallel.

SHORT-CIRCUIT STUDY

This topic presents the study that serves as the basis for the definition of the short-circuit currents that are used for the specification of the SE circuit breakers. Initially, the base power should be chosen and all the impedances considered in the studied system should be referred to the chosen base.

In order to simplify and reduce the calculations, the power of the TF was chosen as the basis. Thus, by applying equation (7), the reactance of the source of supply (FS) of the SE in pu in the chosen base is obtained. The reactance of the TF is already at the base of the system, which is the power of the transformer itself, and it is not necessary to change the base. With respect to the induction motor (M) it is necessary to calculate the power in kVA by applying equation (11)

$$S_M = \frac{CV \times 0.736}{\eta \times cos\varphi} \qquad (11)$$

Substituting the values gets:

$$S_M = \frac{2850 \times 0.736}{0.95 \times 0.85} = 2598\ kVA \qquad (12)$$

Applying the power of the induction motor in kVA and its impedance of 0.17 pu to equation (8) obtains the reactance of the motor on the adopted base. The same equation (8) is used to transfer the 0.045 pu reactance of the auxiliary services transformer to the new base. Thus, the calculated reactances are presented in Table 1.

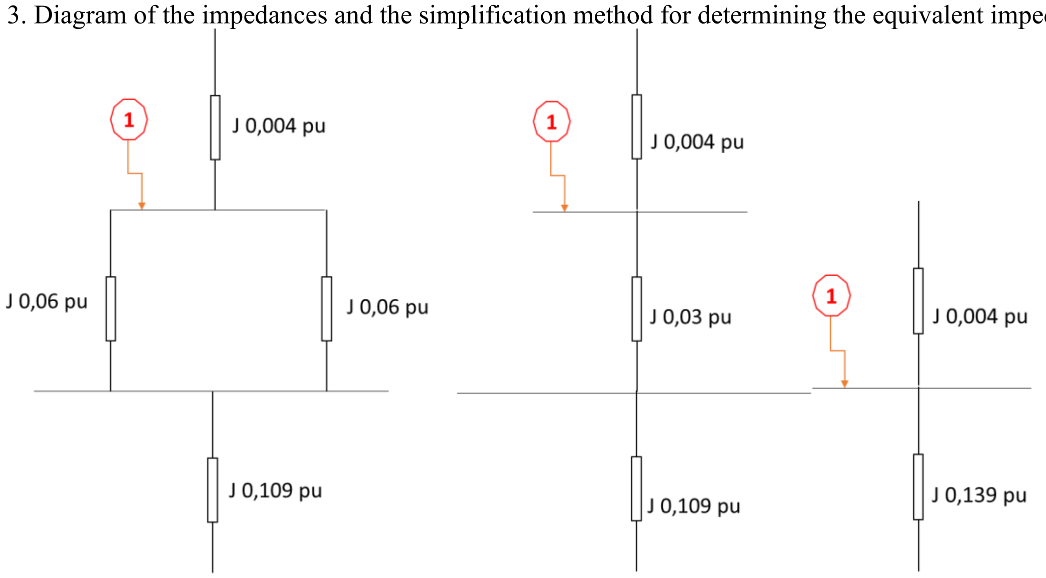
Table 1: Pu reactances at the base of 10 MVA

FS xC	**TF (10MVA) xTF**	**Motor x''_d**	**X equivalent (6 M in parallel) $x''_{d\ eq}$**	**TSA xTSA**	**X equivalence (2 TSA in parallel) xTSAeq**
J 0.004 pu	J 0.06 pu	J 0.654 pu	J 0.109 pu	J 4 pu	J 2 pu

CALCULATION OF THE SHORT-CIRCUIT SUBTRANSIENT CURRENT IN POINT 1

To calculate the short-circuit subtransient current at point 1, it is necessary to transform the single-line diagram in figure 2 into the corresponding impedance diagram for three-phase short-circuit, as shown in figure 3.

Figure 3. Diagram of the impedances and the simplification method for determining the equivalent impedance



The two impedances in the simplified diagram in Figure 3 are in parallel to the short circuit at point 1. The result of this calculation is the equivalent subtransient impedance at point 1, shown in (13).

$$x''_{eq} = j0{,}0039\ pu \quad (13)$$

Using equations (9) and (10) we get the power and subtransient current at point 1 respectively.

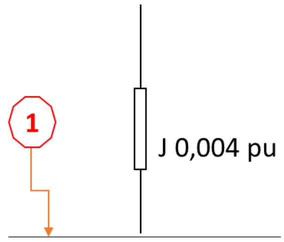
$$S''_{k3} = \frac{10000}{0{,}0039} = 2564\ MVA \quad (14)$$

$$I''_{k3} = \frac{2564 \times 10^3}{\sqrt{3} \times 69} = 21.5\ kA \quad (15)$$

CALCULATION OF THE CURRENT AFTER THE ESTABLISHMENT OF THE SHORT-CIRCUIT STEADY STATE IN POINT 1

The impedance diagram for the calculation of the short-circuit steady state current in point 1 is shown in Figure 4.

Figure 4. Impedance diagram for the calculation of the short-circuit steady state in point 1.



$$S_{k3} = 2500\ MVA \tag{16}$$

$$I_{k3} = \frac{2500\times 10^3}{\sqrt{3}\times 69} = 20.9\ kA \tag{17}$$

MAXIMUM LOAD FLOW

For the sizing of the nominal current of the circuit breaker, it is necessary to calculate the highest current that circulates in the section where it must be installed. According to the single-line diagram in figure 2, the calculation of the highest current circulating in the 69 kV input circuit breaker section is determined by the sum of all the loads of the electrical system, that is, the sum of all motors and auxiliary service loads.

However, it should be noted that the two power transformers were dimensioned to meet the demand of all loads and logically their nominal power is higher than the sum of all loads of the pumping station supplied by the substation. Thus, by dimensioning the nominal current of the circuit breaker by the sum of the nominal power of the power transformers, in addition to standardizing the capacity of the substation equipment, the entire capacity in transformers is released to flow through the system, which may eventually supply a certain increase in load. Thus, the maximum current that circulates in the section to be considered in the nominal design of the circuit breaker is calculated by equation (18).

$$I = \frac{2\times 10000\ kVA}{\sqrt{3}\times 69} = 167.35A \tag{18}$$

69 kV CIRCUIT BREAKER SIZING (52/1)

The calculations involved for the sizing of the circuit breaker are as shown in figure 1. Regarding the studies related to isolation coordination and TRT, reference [10] presents a methodology for these studies.

From the calculated values of 167.3 A for the maximum current circulating in the normal operating period and the value of the short-circuit steady state current of 20.9 kA, the rated circuit breaker current and the rated cut-off current can be determined using Table 2 or any coordination table of the rated current values provided by the circuit breaker manufacturers.

Table 2: Coordination of circuit breaker setpoints

Rated voltage kV (effective)	**Rated short-circuit breaking capacity kA (effective)**	**Rated current A (effective)**					
1	2	3	4	5	6	7	8
72,5	12.5			800	1200		
	16			800	1200		
	20				1200	1600	2000
	31.5				1200	1600	2000
145	12.5	800	1200				
	20		1200	1600	2000	2500	
	25		1200	1600	2000	2500	
	31.5		1200	1600	2000	2500	3000
	40			1600	2000	2500	3000
	50				2000	2500	3000

The rated current to be adopted as well as the rated interrupting current shall be greater than the calculated values of the maximum current in the normal operating regime and the current of the short-circuit standing regime. Thus, using table 2 for the nominal voltage of 72.5 kV, the value of the nominal interrupting capacity immediately higher than the effective value of the calculated periodic component (ca) (*Ik3*) is 31.5 kA and the nominal current coordinated with this value is 1200 A, which easily meets the maximum current that circulates in the stretch under normal operating regime.

Thus, the following nominal values are adopted:

- Rated Short Circuit Breaking Capacity (IIN): 31.5 kA (effective);
- Rated current (IN): 1200 A (effective).

In order to determine the nominal short-circuit establishment capacity, it is necessary to know the asymmetry factor (*f*), which can be calculated by equation (4). Considering the time constant (τ) of 45 ms, the value of *f* calculated by equation (4) is 2.6, as also established in references [6] and [11].

Thus, by applying *f* and the short-circuit subtransient current calculated for point 1 in equation (3), the calculated value of the current is obtained for the determination of the short-circuit nominal establishment capacity of the circuit breaker.

$$I_{fmax} = 2.6 \times 21.5\ kA = 55{,}9\ kA\ (crista) \qquad (19)$$

It turns out that the standardized IIN adopted for the circuit breaker was 31.5 kA. Thus, the standardised short-circuit nominal settling capacity shall be the conforming value (20).

$$I_{Cap\ Est\ Nom\ cc} = 2.6 \times 31.5\ kA = 81{,}9\ kA\ (crista) \qquad (20)$$

The following is the specification of the circuit breaker (52/1) at the substation entrance;

- Rated voltage: 69 kV;
- Maximum rated voltage: 72.5 kV;
- Rated Atmospheric Impulse Withstand Voltage (TSNIA): 350 kV;
- Rated withstand voltage at industrial frequency (TSNFI): 140 kV;
- Nominal frequency: 60 Hz;
- Rated current: 1200 A;
- Rated short-circuit interrupting current: 31.5 kA (effective);
- Nominal short-circuit settling capacity: 81.9 kA (crest);
- Type: SF6 disjunctor;
- Live tank disjunctor;
- Drive type: Tripolar;
- Drive mechanism: Spring loaded automatically by electric motor and manual override;
- Nominal Sequence of Operation: O 0.3s CO 3min CO (fast reclose);
- Rated Interruption Time: 3 cycles;
- Installation: On time.

CONCLUSION

An innovative approach in the sizing of power circuit breakers, presenting a simplified method, is proposed to optimize the selection process of these equipments. For the determination of the short-circuit characteristics, the modified power method is used and dimensioning criteria based on the operation of the electrical system are introduced to define the maximum current in the desired branch for the study.

A test system of a water pumping station composed of a 69 kV substation with selective radial and secondary arrangement is studied. It is concluded that the proposed methodology represents a very useful tool for electrical engineers, assisting them in the selection of power circuit breakers.

A methodological structure like the one used in the article can be adopted for the design of other electrical switchgear. The study can also be extended to size equipment at medium and low voltage.

REFERENCES

1. Junior, C. V. (1988). Disjuntores de Corrente Alternada: Especificação e Aplicação em Sistemas Elétricos de Alta Tensão. *Notas de Aula, Universidade Federal Fluminense, UFF*.

2. Frontin, S. O., et al. (2013). Equipamentos de alta tensão–prospecção e hierarquização de inovações tecnológicas. *Brasília: Teixeira, v. 2000,* 934.

3. Colombo, R. (1986). *Disjuntores de alta tensão.* São Paulo: Livraria Nobel S. A.

4. Lima, G. R., Borges, T. T., Baptista, J. M., Monteiro, P. R., & Lima, L. (2018, May). Virtual reality as a tool for electrical substations teaching. In *2018 Simposio Brasileiro de Sistemas Eletricos (SBSE)* (pp. 1-6). IEEE.

5. Monteiro, P. R. D. (2023). *Introdução à subestação e seus principais equipamentos.* Seven Editora.

6. ABB Power Technologies. (2005). Interruptores tipo tanque vivo — Guía del usuario Edição 3.

7. Associação Brasileira de Normas Técnicas - ABNT. (2020). *NBR IEC 62271-1, Manobra e comando de alta tensão – Parte 1: Especificações comuns para equipamentos de manobra e comando em corrente alternada.* Rio de Janeiro.

8. D'Ajuz, A., et al. (1985). Equipamentos Elétricos – Especificação e Aplicação em Subestações de Corrente Alternada. *Furnas/UFF,* 300 p. Rio de Janeiro.

9. Yuen, M. H. (1974). Short Circuit ABC--Learn It in an Hour, Use It Anywhere, Memorize No Formula. *IEEE Transactions on Industry Applications, 2,* 261-272.

10. Monteiro, P. R. D., et al. (2016). Power system stress analysis for main grid substations in Brazil. *Ingeniare. Revista chilena de ingeniería, 24*(3), 377-391.

11. Norma IEC 62271-100 Edicao 2.1 (2012-09). High-Voltage Switchgear and Controlgear – Part 100: Alternating-current Circuit Breakers.