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CHAPTER 27

Analysis of busbar arrangements in substations: A methodological approach

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ABSTRACT

A substation is the part of a power system, concentrated in a given location, which comprises a set of switching, transformation, compensation and other equipment used to direct the flow of energy and enable its diversification, through alternative routes. According to the 2023 National Energy Balance Report, the final consumption of electrical energy in the country has been growing in recent years, requiring adaptation and expansion of the energy sector, from the generation process, transmission to distribution of electrical energy, emerging the need for investments in the construction of new substations and/or modernization and expansion of existing facilities. Therefore, this study aims to propose a comprehensive methodology for defining the most appropriate busbar arrangement for a given distribution, transmission, and industrial substation project. The methodology is based on qualitative and quantitative criteria, considering elements such as system security, operational flexibility, and availability during maintenance, and thus using a scoring system for each of the criteria taking into account the configuration of the bus arrangement. Additionally, a study of the implementation cost is considered, based on the budget methodology developed by the National Electric Energy Agency (ANEEL). Through these approaches, it is possible to observe that, as the voltage class increases, the system safety and availability requirements also increase, arrangements that more efficiently fulfill these criteria stand out in higher voltage classes, while those that perform poorly in these respects but offer similar operational flexibility excel in lower voltage classes.

Keywords: Substation arrangement, Operational flexibility, System safety, Maintenance availability and Substation cost.

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INTRODUCTION

According to the report of the National Energy Balance (BEN), prepared and published by the Energy Research Company (EPE) [1], whose objective is to present the accounting regarding the supply and consumption of energy in Brazil, it points out that the final consumption of electricity in the country in 2022 grew 2.3%. Thus, according to Monteiro and Miranda [2] the increase in consumption creates the need to adapt and expand the energy sector, from the generation process, transmission to the distribution of electrical energy.

In this context, substations (SEs) become of great relevance, since they are used to direct the flow of energy in a power system, resulting in the need for investments in the construction of new SEs and/or modernization and expansion of existing facilities. [two].

According to Violin; D'Ajuz; Lacorte [3], a substation (SE) is a set of interconnected systems, designed to serve the electrical system in an efficient and economical way. The implementation process is complex and involves several professionals specialized in areas such as civil, electrical, mechanical and communication engineering. The decision to build a new substation arises from studies on the expansion of the electrical system, which identify the need to serve a specific region, city or industrial plant. Crucial aspects are then defined, such as the configuration of the substation bus and the characteristics of the electrical equipment in the switchyard, in accordance with the requirements of the National Electric System Operator (ONS) and ANEEL regulations. The authors also highlight that an ideal substation must offer reliability to the electrical system, which is achieved by the careful choice of its bar configuration and that, in addition, provide facilities for maintenance, expansions and good visibility of its components, aspects guaranteed by a well-designed physical project, they also highlight that the maneuvering yard equipment must be robust enough to withstand the demands of the system, and the command and protection system must operate safely and effectively. Thus, the authors conclude that a well-designed and executed substation plays an essential role in the reliable operation of the system.

The Brazilian Standard NBR 5460 [4] defines that an SE constitutes an essential part of a power system, centralized in a specific location. It mainly encompasses the connection points of transmission and/or distribution lines, accompanied by maneuvering, control and protection devices. This covers not only the electrical aspects, but also the civil structures and necessary assemblies, and may also include other equipment relevant to its operation.

The standard also classifies SEs according to function, form of operation and construction types. The defined function types are:

a) SE Transformer: It is the one that converts the supply voltage to a different level, higher or lower, being designated, respectively, SE Step-Up Transformer and SE Step-Down Transformer [5].

- Step-down SE: A transformer SE that reduces the voltage level generated by an electrical energy source and distributes the associated power to overhead and underground distribution networks, supplying substations with a lower voltage level [6]. Therefore, in this type of SE, the output voltage is lower than the input voltage.
- Step-up SE: A step-up transformer SE has the function of raising the voltage level generated by an electrical energy source and distributing the associated power to transmission lines with higher voltage than the original [6]. In other words, the output voltage is greater than the input voltage.

b) SE converter: These SEs are intended to convert alternating current to direct current, or vice versa, in addition to making it possible to change the frequency of alternating current from one value to another [6].

c) Switchgear IF: Is one that interconnects supply circuits under the same voltage level, enabling their multiplication. It is also adopted to enable the sectioning of circuits, allowing their energization in successive sections of shorter length [5]. These SEs have the main objective of changing the configuration of an electrical system by modifying the interconnections between transmission lines.

It is worth highlighting that, with the advancement of technology and installation methodology, currently, regardless of the construction type of the substation, the way of operation relies on a digital supervisory system. It is not common for operators to be present at the substation, except in cases of maintenance.

Mamede [6] proposes a subclassification into two types of construction for substations in external environments: bare busbars and conventional installation, or construction using compact insulated busbars. The author also highlights the classification of substations according to the means of insulation, which can be by air insulation (AIS - Air insulated substations), total gas insulation SF_6(GIS - gas insulated substations) or in a hybrid form, which combines substation technology air-insulated with air-insulated substation technology SF_6.

Monteiro and Miranda [2] define that it is important to take into account several factors when choosing the arrangement of an SE, including simplicity, availability of supply, economy and security, as required by the function and relevance of the SE in the project. The authors also discuss the busbar arrangements most commonly used in substations, covering options such as: simple busbar; main and transfer bus; double busbar with single circuit breaker; ring bus; bus breaker and a half; and double busbar with double circuit breakers. The authors also highlight that in industrial distribution contexts, excluding the input substation, whose configuration depends on the voltage to which it is connected, the arrangements usually used are radial, selective primary, and selective secondary, or combinations of these.

The authors state that substation arrangements can present different levels of complexity, making it important to select the appropriate scheme, given its direct influence on the performance of the substation, where they give the example of simple buses which, in general, are not used in substations of great importance, since this scheme is less flexible, depending on a single main bus, this makes the system more susceptible to frequent shutdowns, as in cases of failures or the need for maintenance at the substation, it is necessary to shut it down completely . However, they highlight that the advantage of this type of arrangement is its low cost. The study conducted in [2] concludes that in most SEs built for transmission, distribution and industrial sectors, air insulation is the standard due to lower initial costs. However, in specific situations, other technologies have proven to be viable options.

Submodule 2.6 of the Network Procedure formulated by the ONS [7], establishes the minimum requirements for SEs, applicable both to transmission facilities that are part or will become part of the basic network, as well as to international interconnections and generation agents. These guidelines are presented below.

Air-insulated SEs must adopt one of the following configurations for the busbar arrangements, depending on their voltage class [7]:

i) Voltage bus equal to 230 kV: double bus arrangement with single four-key circuit breaker; or
ii) Bus voltage equal to or greater than 345 kV: double bus arrangement with circuit breaker and a half.

For alternative bus arrangements, including those with isolation technology in SF_6, the submodule determines that they can be adopted, provided that analyzes of reliability, operational flexibility and availability (scheduled and unscheduled) demonstrate performance equal to or greater than that of the arrangements defined in (i) and (ii) [7,8].

In submodule 2.6 [7], it is also established that, for buses with voltage equal to or greater than 345 kV, it is possible to initially adopt the simple ring bus arrangement, as long as the physical layout of the SE buses follows the guidelines defined in points (i) and (ii). Furthermore, for 230 kV buses, in SEs that operate as simple radial systems, it is permitted to opt for the main bar and transfer arrangement, as long as the physical design of this bus is designed to enable the transition to the arrangement specified in items (i) and (ii).

Therefore, this article aims to offer a holistic view of the relevance of SEs in the electrical system, providing solid support for decision-making in electrical infrastructure projects. A methodological approach for the analysis of busbar arrangements of distribution, transmission and industrial SEs is proposed based on technical and economic criteria.

METHODOLOGY

SEs, as main points of interconnection of transmission, distribution and industrial systems, have a great influence on the reliability of these systems. The choice of arrangements and maneuvering schemes must be made so that component failures do not compromise the safety of the system as a whole. This establishes the need to determine the reliability of each proposed configuration in order to select the most technically suitable arrangement. When choosing the configuration for a new transmission system SE, it is important to clearly define the technical and economic criteria that serve as a basis for comparing the different busbar arrangements considered. In general, basic characteristics to consider include [9]:

i) System security;
ii) Operational flexibility;
iii) Ease of maintenance of components;
iv) Simplicity of protection and control;
v) Available space and ease of expansion;
vi) Cost.

Among these characteristics, only two, system security and cost, have a quantitative element of comparison. The others reflect the experience and operational practice of the different companies. However, to simplify the analysis when choosing a substation bus configuration, four fundamental parameters are considered for the choice. The methodology adopted for the development of this work comes from the work entitled " Circuit Configuration Optimization" carried out by CIGRÉ's Joint Working Group B3/C1/C2.14, in which Lingner and others [10] establish a scoring system, based on the importance of each parameter, being then quantitatively only the cost criterion. Below are the fundamental parameters selected for analysis and evaluation, with their definitions.

SYSTEM SECURITY

This parameter evaluates the ability of the SE configuration to maintain a reliable supply. We examine the impact of equipment on the electrical grid, assuming correct operation of control and protection systems. This involves considering conditions such as circuit breaker tripping in the event of a primary failure and the consequences when the circuit breaker fails to open.

In Table 2.1, numbers 1 to 6 represent different levels of impact or severity. A score of 1 is given when an outcome is seen as the worst, indicating that it had the greatest negative impact, on the other hand, a score of 6 is given when a result is seen as the best, indicating that it had the least or no negative impact. negative impact.

Table 2.1 - Assessment criteria with system security scores

Punctuation	Possible consequences for the network due to a primary failure	Possible consequences for the network due to a primary failure followed by failure of the circuit breaker to open
1	Possible loss of entire substation	Loss of entire substation
two	Loss of one or more feeders, but not the entire substation	Loss of more than one feeder or the entire substation
3	Loss of one or more feeders, but not the entire substation	Loss of more than one feeder, but not the entire substation
4	Loss of a feeder	Loss of a feeder and always an extra feeder, but not the entire substation
5	Loss of none or one feeder	Loss of a feeder and possibly an additional feeder, but not the entire substation
6	Loss of none or one feeder	Loss of a feeder

Source: Adapted from [10].

OPERATIONAL FLEXIBILITY

Refers to the ability of the substation configuration to rearrange feeders or divide the substation into multiple parts as necessary. This involves the substation's ability to perform breakdowns, which can occur in two distinct ways: energized and non-energized.

For energized dismemberment, the reconfiguration of connections is carried out while the substation remains energized, ensuring continuity of energy supply during the process. While the unenergized teardown, specific parts of the substation need to be temporarily shut down to perform the teardown. This capacity is important to meet the possible dynamics of the electrical grid and ensure efficient operation.

Table 2.2 presents the evaluation criteria with the corresponding score for operational flexibility. It is important to highlight that, in addition to the division of the substation, the option to determine which part of the divided substation each circuit will be connected to contributes to a higher score in the configuration. This is especially significant in specific situations where choosing to connect a circuit in a specific part of the substation may be advantageous.

Table 2.2 - Assessment criteria with scores for operational flexibility

Punctuation	Definition
1	Can't split
two	Division not energized (only with disconnector). No flexibility
3	Energized division (with circuit breaker). No flexibility
4	Energized division (with circuit breaker). Low flexibility
5	Energized division (with circuit breaker). High flexibility, maneuver with disconnector
6	Energized division (with circuit breaker). Highest flexibility, operation with circuit breaker

Source: Adapted from [10].

AVAILABILITY DURING MAINTENANCE

This parameter checks whether the substation configuration allows the feeders to be kept energized while maintenance activities are carried out on disconnect switches and circuit breakers. During maintenance, the bus disconnector switch is a critical point as the relevant bus needs to be de-energized.

The scores, listed in Table 2.3, range from 1 to 7 and have specific meanings. A score of 1 represents the worst consequences on the network, indicating the interruption of the entire substation. On the other hand, a score of 7 indicates the least serious consequences on the network. In this scenario, no network element would be disconnected and the network topology would not be weakened. Therefore, the operation of the substation would not be significantly affected.

INVESTMENT COST

This factor analyzes the total investment required to implement the substation, including the costs associated with command, protection, control and communications equipment. Understanding the complexity involved in preparing budgets for substations and with the objective of establishing the standardization of concepts and values, ANEEL establishes a methodology based on the concept of modulation.

Table 2.3 - Assessment criteria with scores for availability during maintenance of circuit breakers and disconnecting switches

Punctuation	Maintenance of	Consequence
1	Any disconnect switch connected to the bus	Shutdown of the entire substation
two	Bus disconnect switch	Shutdown of the entire substation
3	Disconnect switch connected to the bus or bus disconnect switch	Shutdown of half of the substation
4	Any disconnect switch connected to the bus	Disconnection of a bus and corresponding circuit. Remaining circuits in operation.
5	Any disconnect switch connected to the bus	Disconnection of a bus and corresponding circuit. Remaining circuits in dual-bus operation
6	Any disconnect switch connected to the bus	Shutdown of a bus and all circuits in operation on the same bus
		Open Ring
		Substation breakdown or loss of configuration
	Circuit breaker	Loss of substation setup or split, but all circuits in operation
7	Any disconnect switch connected to the bus	Shutdown of a bus. All remaining circuits in operation
	Circuit breaker	All circuits remain in operation

Source: Adapted from [10].

The approach consists of detailing and quantifying the modules based on the materials, equipment and services necessary to carry out the project. Annex I of Order No. 3,246 of November 16, 2022, from ANEEL [11], presents this methodology. The modulation concept used in the ANEEL Reference Price Bank involves the subdivision of the substation into smaller units, each representing distinct sectors in terms of function, operation and physical structure. Therefore, a substation is composed of a variety of modules that are essential for its operation, including those related to line inputs, equipment connections and infrastructure [12,13].

Modular units, regardless of voltage class and type of arrangement, are subdivided into three types: Infrastructure Module, Maneuver Module and Equipment Module. The definition of these units and the parameters used in preparing budgets is based on the minimum requirements established in the Network Procedures [7].

The ANEEL resolution also establishes fundamental criteria for the classification of substations, which is of great importance for preparing budgets and planning electrical installations. This categorization is based on two main factors, voltage level and physical arrangement, as shown in Table 2.4.

Therefore, the substation bus arrangements are divided into two blocks for more accurate analysis and comparison.

The first block is composed of the Single Bus (BS), Main and Transfer Bus (BPT) and Double Bus with Five Switches (BD5) arrangements, classified with voltage levels of 69 kV and 138 kV. While in the second block there are the physical arrangements in the configuration of Ring Bus (AN), Double Bus with Circuit Breaker and a Half (DJM) and Double Bus with Double Circuit Breaker (BDDD), which are analyzed and compared at voltage levels of 440 kV and 500 kV.

Table 2.4 - SEs arrangements according to voltage level

Voltage (kV)	B.S.	BPT	BD5	AN	DJM	BDDD
13.8	X	X				
69	X	X	X			
138	X	X	X			
230		X	X			
345				X	X	
440				X	X	X
500				X	X	X
750					X	X

Source: Adapted from Annex I of Order No. 3,246 of November 16, 2022 from ANEE [11].

It is important to highlight that defining an evaluation criterion based on an important characteristic, such as operational issues or maintenance procedures, facilitates the choice of the bus arrangement of an SE in the most appropriate way.

This adopted methodology, focused on network performance, allows comparison between configurations, regardless of the technology used. However, the choice of technology should not be ignored, as it can influence the type of configuration or even result in new arrangements [10].

COMPARATIVE ANALYSIS OF THE MAIN SUBSTATION MANEUVERING SCHEMES

Each array received specific scores for system security criteria, which reflect its ability to handle normal and faulty conditions. The score assigned was shown in Table 3.1.

Table 3.1 - Score of bar arrangements for the system Safety criterion

	B.S.	BPT	BD5	AN	DJM	BDDD
Punctuation						
1	1	1				
two			two			
3						
4				4		
5					5	
6						6

Source: Adapted from [10].

When evaluating the safety of the service, it is important to note that, when analyzing the configurations in terms of functionality and possible consequences, it is clear that double busbar systems do not guarantee the total prevention of loss of SE in situations of additional circuit breaker failure. Furthermore, as a higher level of system security is sought, there is an increase in the amount of equipment required for SE. This increase in complexity and number of devices consequently results in higher implementation costs to ensure more robust security of the electrical system.

Availability assessment during maintenance analyzes how the network is affected when circuit breakers and disconnect switches in the SE are out of operation. During maintenance, the bus disconnector switch is a critical point as the relevant bus needs to be de-energized. Multi-busbar configurations improve availability during bus-disconnect switch maintenance, but this comes with additional cost and space footprint.

For the availability criterion during maintenance, the scores assigned are as shown in Table 3.2.

The high score of the BDDD arrangement in availability during maintenance is attributed to the specific characteristic of this arrangement, its redundancy of circuit breakers, which guarantees the continuous availability of the system.

Other arrangements with high scores are BD5, AN and DJM. The BD5, due to the large number of disconnecting switches, allows for different configurations, reorganizing itself during the maintenance period. On the other hand, AN and DJM configurations, as well as BDDD, also provide a certain level of redundancy, resulting in a good score.

BPT offers the ability to transfer load to a backup bus during maintenance, thus maintaining service continuity, however no circuit breaker is available to protect the circuits and the process for replacing the tie breaker is difficult and can lead to errors of operation. This transfer capacity together with the difficulty of operation contributes to a lower score in the criterion.

Finally, the BS configuration scores lower due to its limited maneuverability and redundancy. During maintenance, there may be a need to completely stop service rather than transferring load to a backup bus.

Table 3.2 - Score of bar arrangements for the Availability criterion during maintenance

Punctuation	B.S.	BPT	BD5	AN	DJM	BDDD
1	1					
two						
3		3				
4						
5						
6			6	6	6	
7						7

Source: Adapted from [10].

To assess operational flexibility, Table 3.3 presents the score for this criterion according to the bar arrangements studied.

Table 3.3 - Score of bar arrangements for the criterion of Operational Flexibility

Punctuation	B.S.	BPT	BD5	AN	DJM	BDDD
1	1					
two						
3		3				
4			4	4	4	
5						
6						6

Source: Adapted from [10].

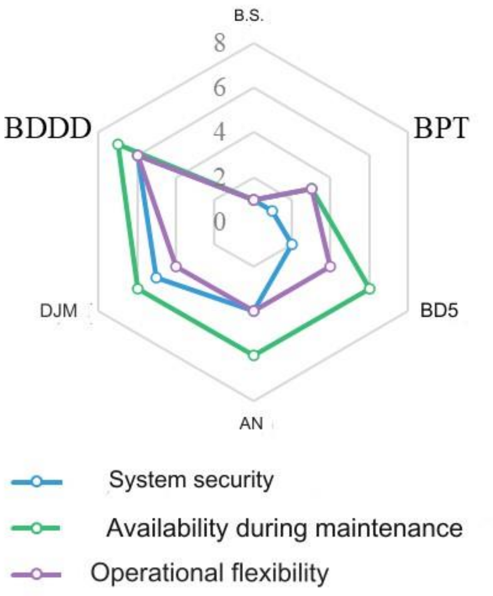
Again, the highest score is given to the double busbar arrangement with double circuit breaker, for the same reason as the previous criteria, this is due to its ability to provide circuit breaker redundancy, ensuring the presence of two independent interrupting devices. This feature increases operational reliability, allowing faults in circuit breakers to be isolated without affecting the entire substation. Therefore, this configuration has the capacity for selective isolation and adaptation to different operating conditions.

In Figure 3.1, it is possible to visualize all bus arrangements accompanied by the evaluation criteria. A trend can be observed when seeking greater security in the system, less interruption and greater flexibility. The BDDD, AN and DJM arrangements stand out as the best options, being recommended for busbars with voltages equal to or greater than 345 kV, which are substations that are of great importance.

Therefore, for the Simple Busbar arrangement, it is suggested to install it at voltages equal to or lower than 138 kV. This recommendation is aimed at substations where the temporary loss of the substation, whether due to failure or maintenance, does not cause significant impacts in its absence. It is advisable that facilities of this type adopt a maintenance and operation plan, aiming to minimize the period of unavailability in emergency situations.

In the voltage class equal to or less than 230 kV, BD5 arrangements, or the variation, the Double Four-Switch Busbar (BD4), are recommended.

Figure 3.1 - Scoring of evaluation criteria for bus arrangements



Source: Prepared by the author.

For cost analysis, Figure 3.2 shows the costs of implementing the switchyard for voltages of 69 kV and 138 kV of SEs arrangements with BS, BPT and BD5. It is observed that the increase in implementation cost when going from the primary voltage of 69 kV to 138 kV is around 74% for all arrangements, therefore, the analysis for one input voltage level is valid for the other.

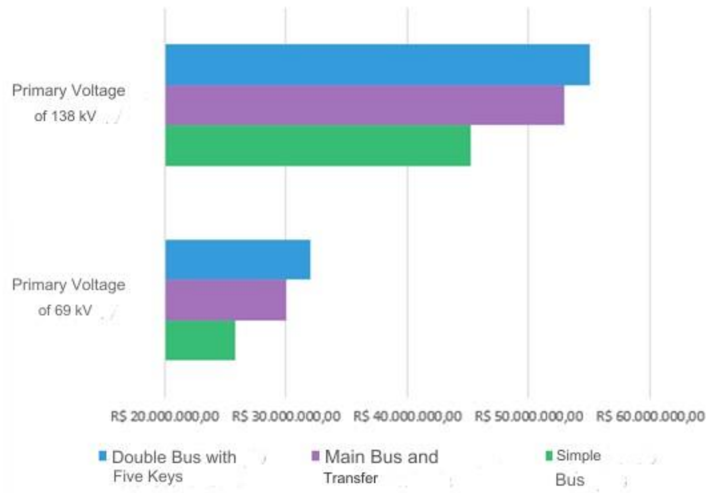
To build the BS array at 69 kV, approximately R$ 25,779,743.09 are required; for BPT, the cost is R$29,997,407.23; while for the arrangement in BD5, the value is R$ 31,960,215.74. The difference between BS and BPT is R$4,217,664.14 in the project, and between BS and BD5 is R$6,180,472.65. This difference is mainly related to the cost of the bus interconnection circuit breaker that the BPT and BD5 arrangements have, as well as the presence of a greater number of disconnecting switches compared to the BS.

The difference between BPT and BD5 is R$ 1,962,808.51. It is also worth mentioning that the BPT and BD5 arrangements occupy an area of approximately 13,200 m² for 69 kV and 21,000 m² for 138 kV, while the single bar occupies an area of 12,320 m² for 69 kV and 19,200 m² for 138 kV. This factor is important to be considered in the SE project.

The analysis for choosing the best arrangement for the 69 kV or 138 kV yard of a SE depends on the designer and the criterion that is most important to the SE. Furthermore, it is important to consider whether there are future expansion plans for the SE. It is observed that the cost difference between BPT and BD5 is relatively small compared to the difference between each of these configurations and the BS arrangement. Therefore, when choosing between BPT and BD5, it is recommended to be based on the advantages that each arrangement will provide and the specific priorities of the project, as BD5 performed better in the evaluation criteria compared to BPT. As a result, these arrangements offer greater operational flexibility and reliability to the power system compared to the BS arrangement.

Considering the described advantages of the BPT and BD5 arrangements in relation to the BS arrangement, the additional amounts of R$4,217,664.14 and R$6,180,472.65 in the project can be justified by the benefits that are provided to the system over the years , being able to serve the load more efficiently and safely.

Figure 3.2 - Implementation Costs at 69 kV and 138 kV for BS, BPT and BD5



Source: Prepared by the author.

For the analysis of ring bus (AN), double bus with breaker and a half (DJM) and double bus with double breaker (BDDD) arrangements, Figure 3.3 presents the implementation costs for voltages of 440 kV and 500 kV. Observing the same point of the previously analyzed bus set, the increase in implementation cost when going from the primary voltage of 440 kV to 500 kV is around 25% for all arrangements, therefore, as in the block previously evaluated, the analysis for one input voltage level is valid for the other.

The AN arrangement has an implementation cost of R$81,588,905.35 for 440 kV and R$100,439,135.80 for 500 kV. For the BDDD arrangement, the investment is R$ 102,180,023.82 for 440 kV and, for 500 kV, it is R$ 127,592,057.40. Finally, the DJM arrangement costs R$82,936,572.89 and R$101,759,787.74 at 440 kV and 500 kV, respectively.

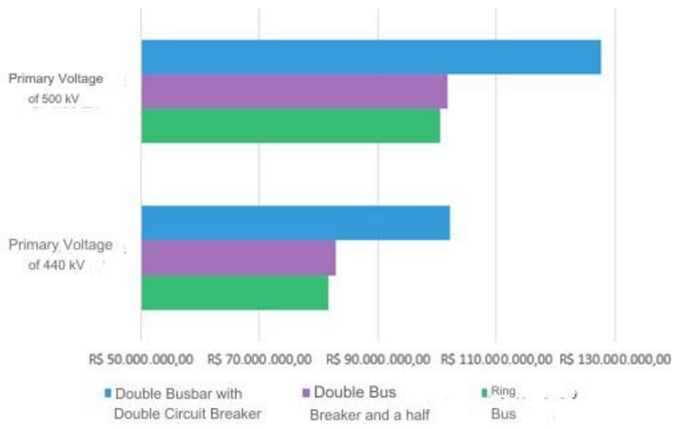
It appears that AN has the lowest investment in cost, with a difference in relation to BDDD of R$ 20,591,118.47 and between DJM of R$ 1,347,667.54, for the input voltage of 440 kV. However, for AN, installing more than five circuits is not recommended. However, it is possible and usual to initially design an AN and when more than five circuits are needed, transform it into a DJM.

Comparing the AN arrangement with BDDD and DJM, it can be seen that for the operational flexibility criterion, BDDD has a better score, while for the system security criterion, AN has a lower score compared to both BDDD and the DJM. Thus, for cases in which it is possible to opt for DJM or AN, the installation of the breaker and a half bus can be advantageous, as the cost difference is significantly low, and can offset in the long term the performance benefits of the breaker and a half bus arrangement. quite.

When comparing the costs of implementing BDDD and DJM, a difference of R$ 19,243,450.93 is observed. Considering the advantages analyzed as shown in Figure 3.1, BDDD has a better score in the system safety criteria, availability during maintenance and operational flexibility than the DJM arrangement. Therefore, because this cost difference is significant, it is recommended to evaluate how important these advantages are for the SE project.

Therefore, if we only consider the implementation cost, the AN arrangement becomes better, however, it is important in the initial phase of the project to consider which path is more advantageous in the long term and which criteria are indispensable, especially if the substation has a plan of future expansion.

Figure 3.3 - Implementation Costs at 440 kV and 500 kV for AN, DJM and BDDD

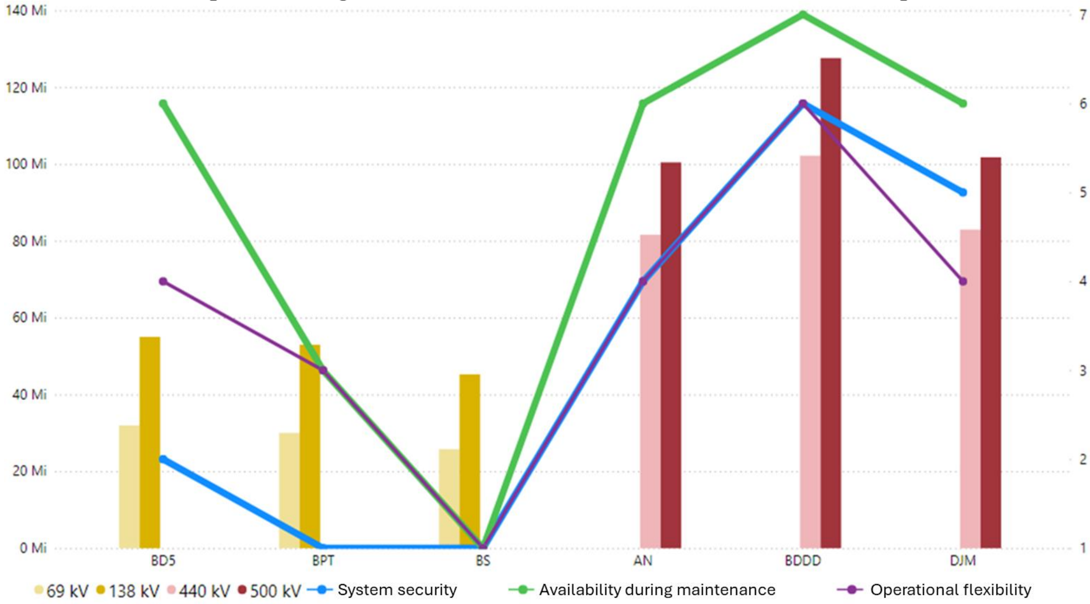


Source: Prepared by the author.

After an in-depth analysis of each criterion and the evaluation of the bus arrangements, it becomes evident that each configuration presents its distinct characteristics in relation to safety standards, operational flexibility, maintenance availability and costs associated with implementation. It is highlighted that the BDDD, AN and DJM arrangements have emerged as options that offer greater security, availability and operational flexibility.

On the other hand, the BS arrangement has lower initial costs and proved to be more limited in terms of security and operational flexibility. Its application is recommended in less complex SEs, where service interruption during scheduled maintenance is acceptable. Figure 3.4 presents the qualitative analysis and implementation costs for the studied arrangements.

Figure 3.4 - Implementation costs and evaluation criteria for bus arrangements



Source: Prepared by the author.

This is a graph that displays the costs for the primary voltages of 69 kV, 138 kV, 440 kV and 500 kV, along with the score of the qualitative criteria associated with each bus arrangement.

Concluding, then, that the choice of the ideal bus arrangement must be guided by the specific needs of each ES. Therefore, it is recommended to classify the substation into one of the categories such as transformation SE, maneuver SE or generation SE, and thus assign different weights to the methodology criteria based on these categories. This links the selection of busbar arrangement to the specific function of the substation in the power system. In a high-capacity generation substation, the System Safety criterion must be more considered, as it is necessary to guarantee supply for as long as possible, while in a maneuvering substation, Operational Flexibility may have greater importance.

Table 2.4, which summarizes the substation arrangements according to voltage level, justifies the bar configuration criteria established by the ONS. It highlights that, as the voltage class increases, system safety and availability requirements also increase, arrangements that more efficiently meet these criteria stand out in higher voltage classes.

CONCLUSION

This study aimed to present criteria to guide the evaluation and comparison of ES configurations, through an appropriate quantifiable process to meet the specific needs of each ES, adopting the most efficient bus configuration for the type of installation. The work defined and described the classic and most used bus arrangements for SEs, which were then used to apply the methodology.

The methodological approach of this work was based on the evaluation of three fundamental factors that influence the SE configuration: service security, analyzing the SE configuration in terms of availability of supply to the network; availability during maintenance, examining the ability of the SE configuration to keep circuits energized during maintenance of disconnect switches and circuit breakers; and operational flexibility, analyzing the capacity of the SE arrangement to allow the reorganization of circuits or the SE to be divided into two or more parts.

The three qualitative analysis criteria were assigned a scoring system to compare them in relation to each of the bar configurations. Thus, an objective classification matrix was generated, considering all classifications and scores of the different configurations that are used in different applications. This matrix can be used as an aid in a decision process, during the selection or optimization of a SE bus configuration. It is important to highlight that the matrix should only be used as a guideline and not in a dogmatic way.

Furthermore, an implementation cost assessment was carried out, adopting the methodology for implementation costs used by ANEEL in its budget simulator for SEs and transmission lines. This methodology is based on SE modulation.

In addition to the four criteria discussed in this work, it is necessary to recognize that there are specific technical implications related to the project and needs of each planned SE. The choice of installation technology, such as compact, conventional, gas-insulated SF_6 or hybrid modules, and the consideration of the area available for installation are examples of aspects not detailed in this study, but which play a vital role in the specific project and must be considered by the designer.

Therefore, the main contribution of this work is to provide engineers with an additional tool in choosing the most appropriate bus scheme for an SE. By applying the methodology, it was possible to verify that each configuration presents its characteristics in relation to security standards, operational flexibility, maintenance availability and costs associated with implementation. Noting that as voltage increases, system security and availability requirements also increase. More efficient configurations in these criteria stand out in higher voltage classes.

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