

Reliability and Cost-Effectiveness Analysis of Various HV Substation Configurations

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SUMMARY

Reliable power supply is one of the crucial factors for the development of any industry. Different technologies as well as configurations are available when it comes to investing in new electrical assets. According to [1], the circuit configurations of high voltage substations are strongly influenced by many factors, such as operational requirements, security standards, availability, maintainability, etc. There is always a trade-off between the technical requirements and the cost of investment. This paper aims to quantify the availability of a switchyard with two lines and two transformer bays for various switching configurations. Once the overall availability is determined, the decision for the selection of a switching configuration is made based on the cost-benefit analysis.

The voltage rating of a primary substation is decided based on the scale of an industry. Switching configuration is one of the major factors affecting the overall availability of the substation. Each switching configuration has its own pros and cons in terms of its operation, reliability and investment cost. It is impossible to achieve 100% availability of a substation with any kind of switching scheme. Availability and investment cost of a substation vary with the choice of the configuration and substation technology. There are mainly three available technologies - Air Insulated Switchgear (AIS), Gas Insulated Switchgear (GIS) and Mixed Technology Switchgear (MTS). However, due to difference in the maintenance strategies and procedures, costs vary among different technologies. This paper focuses on AIS, as the most common one seen in practice. Comparison analysis of different technologies is not within the scope of this paper.

In this paper, a 220/66kV AIS substation for an upcoming process plant is under consideration. The scope of this paper is limited to assess the availability of primary side of the substation. There are two-line bays and two transformer bays in the 220kV switchyard. Down-stream to the 66kV side is not taken into consideration for the analysis purpose. This analysis is applicable for higher voltage-level substations as well (EHV and UHV), since their reliability is of a very high importance and the switching configurations are the same.

KEYWORDS

Power Systems Reliability, Substations, Busbar configurations, Switchgear, Availability, Equipment failure, Downtime, Outage cost, Cost-benefit analysis.

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INTRODUCTION

This paper is divided into four parts. In the first part, the methodology to calculate the availability and the formulated assumptions are explained. The second part highlights various switching configurations under consideration, along with some examples to construct the availability block diagram with the goal of computing the availability of different busbar configurations. The results are explained in the third part, followed by the cost-benefit analysis to make the decision in the fourth part.

PART I – METHODOLOGY AND ASSUMPTIONS

The availability of individual components in the substation is derived from the data of Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR). In order to compute the overall availability of any system, the system components can be modelled as a series and parallel connection of their availability blocks. If any of the components fails in the series connection, the whole system fails. On the contrary, in parallel connection, the whole system fails only if all the components fail.

In order to compute the overall availability of a switchyard, several assumptions are made to simplify the calculations while retaining as a precise model of reality as possible.

1. Only major faults are considered, such as flashovers, mechanical breakdowns, ground faults, short circuits, explosions etc. Minor faults such as communication/protection faults are not considered. The same applies to faults in joints, short conductors/jumpers, string insulators, and independent multiple simultaneous faults.
2. It is considered that substation has full redundancy of supply. Only one transformer and one line are enough to provide the required power to the industry.
3. If a fault happens and it is possible to isolate the fault by proper switching of disconnectors and circuit breakers in order to re-establish the supply, the interruption time is considered to be 30 min, hence the availability shall be derived accordingly. The 30 minutes are considered for the decision-making process and the operation itself. Such components are highlighted in **BLUE** colour in the availability block diagrams in the following section.

PART II – SUBSTATION CONFIGURATIONS AND RELIABILITY CALCULATIONS

The focus of this paper is to make a comparison among several switching configurations and find optimal one in the reliability aspect. The substation under consideration consists of two incoming lines coming from a different power source and two parallel transformer bays, which are capable of feeding entire load independently. Six common switching configurations are taken into consideration:

Table 1: Substation Configurations, 1 TSEK=1000 SEK≈139.70 CAD≈103.87 USD≈92.45 EUR as on 11-05-2019

Equipment ²	Unit cost [TSEK]	Substation Configurations					
		(A)	(B)	(C)	(D)	(E)	(F)
SA	120	4	4	4	4	4	4
VT	320	2	2	2	2	2	2
DS/ES	390	6	7	8	14	12	16
CB	700	4	4	5	5	5	9
CT	230	4	4	5	4	5	9
Power Trafo	4750	2	2	2	2	2	2
Busbar (BB)	625	1	1	1	2	2	2

- (A) Single Busbar (SBB)
- (B) Single Busbar with Section Isolator
- (C) Single Busbar with Sectionalizer
- (D) One Main and Transfer
- (E) Double Busbar (DBB) with Single Circuit Breaker
- (F) Double Busbar with Double Circuit Breaker

Each of the mentioned configurations has a different number of components and every component has its corresponding price. It is assumed that same type of individual

² SA-Surge Arrester; VT/CT-Voltage/Current Transformer; DS/ES-Disconnecter/Earthing Switch; CB-Circuit Breaker

equipment would be used in every configuration. Table 1 represents the summary of the price and number of components in the configurations. The prices of equipment are obtained from Swedish TSO Svenska Kraftnät, for current market situation (September 2018, based on industry contracts). Based on the methodology and assumptions derived in the previous section, the reliability block diagram for the configurations is prepared. Overall availability and downtime have been calculated. The reliability data of components is obtained from CIGRE/CEA references [2], [3], [4] and [5], for 220 kV switchgear and major fault events. To demonstrate the process of building the block diagrams, two examples are discussed in this paper.

- **Single Busbar with Sectionalizer (C)**

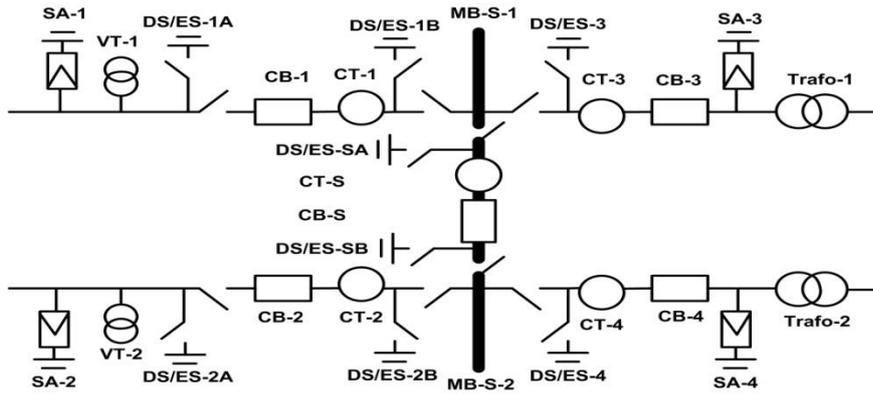


Figure 1: Single line diagram of (C)

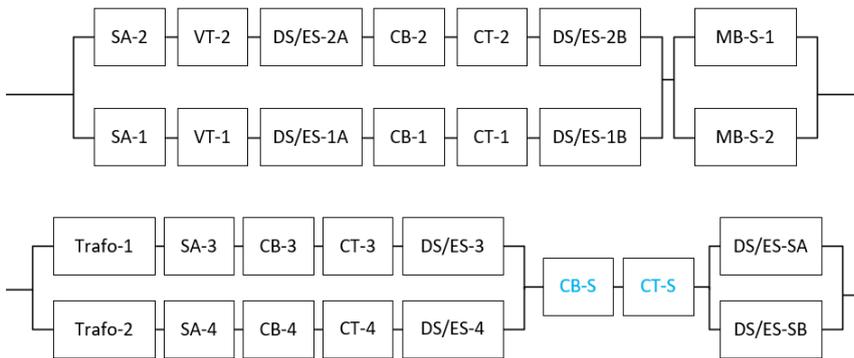


Figure 2: Reliability block diagram of (C)

This configuration is an upgrade of configuration (B). Figure 1 represents the single line diagram of the system.

The reliability block diagram is created based on the described methodology and the assumptions. Figure 2 represents the reliability block diagram for (C).

As only one line is sufficient to supply the full load to the industry, the components in the line bays are connected in parallel. Failure of both lines will cause the total outage of the switchyard. The same logic also applies for the transformer

bays. The main busbar is divided into two parallel blocks since it can be effectively operated like two independent busbars due to the presence of CB in the sectionalizer, allowing fast isolation of a fault in one part of it. Two disconnectors DS/ES-SA and DS/ES-SB are located in the sectionalizing bay. If any of them fails, it is possible to continue supply, since the CB will be able to isolate the fault. However, if the current transformer (CT-S) or circuit breaker (CB-S) fails, the fault cannot be immediately isolated by any protection/control action, hence temporary outage will occur. However, due to the available disconnectors, fault can be isolated and the substation can be re-energized, which is assumed to take 30 min for major fault events. Such components are presented in blue colour.

Configuration (C) offers superior features than (A) and (B). Configuration (B) does not have a circuit breaker in sectionalizer bay, therefore, a temporary shutdown is required to operate the off-load disconnector. Furthermore, any fault in the section disconnector will result in the complete shutdown of the station.

- **Double Busbar with Single Circuit Breaker (E)**

This configuration introduces more components and another busbar system and it is considered to be a very efficient solution. Its single line diagram is presented in Figure 3 and its reliability block diagram is represented in Figure 4. The main difference with this configuration is the existence of two

independent busbar systems, each having its own disconnector with corresponding incoming line and transformer bay. This allows high redundancy due to multiple available power flow paths.

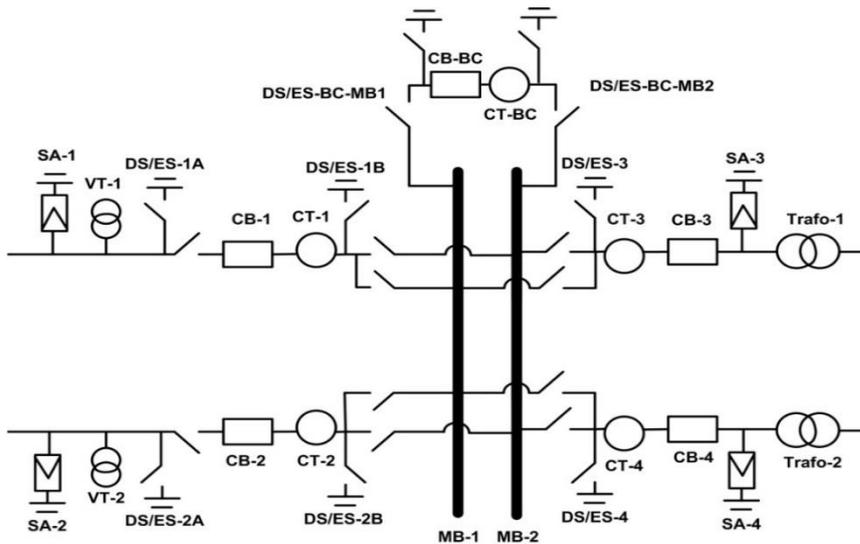


Figure 3: Single line diagram of (E)

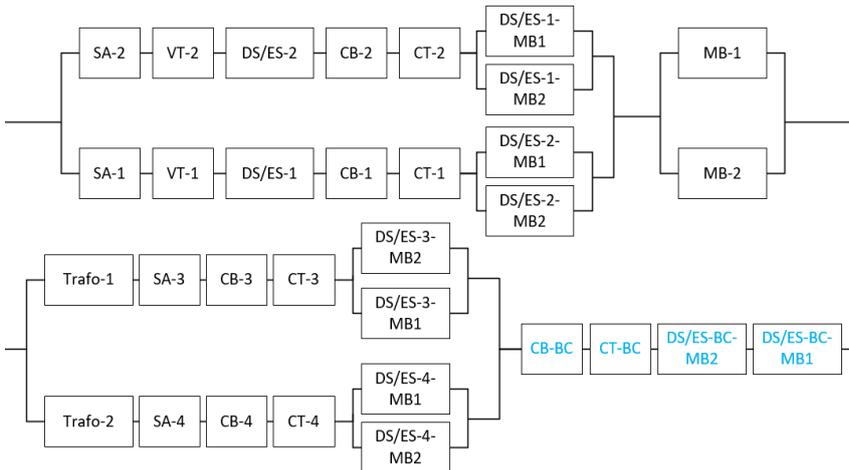


Figure 4: Reliability block diagram (E)

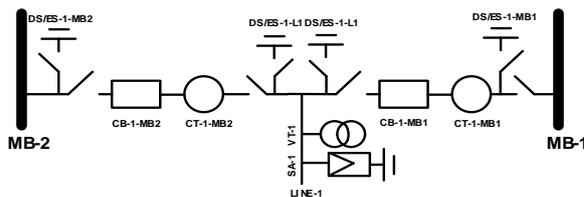


Figure 5: Single line diagram of (F)

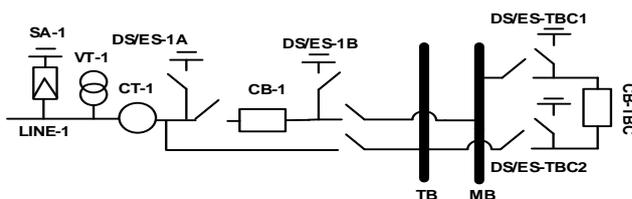


Figure 6: Single line diagram of (D)

However, the components located in the busbar coupler will cause a power outage if any of them fails. The fault will be temporary since it is possible to use a proper switching procedure to isolate the fault and restore the power flow. Rest of the configuration is connected in parallel blocks, as with the previous configurations.

The single line diagram of one bay in configurations (F) and (D) are represented in Figure 5 and Figure 6, respectively, in order to make a comparison of the two. Configuration (F) is an upgrade of (E). In addition to the busbar redundancy, this type of configuration also provides circuit breaker redundancy for each bay and hence, the overall availability of this configuration is expected

to be the highest amongst the analysed configurations. However, it also has the highest cost of investment due to the increased number of switchgear components present in the configuration. On the other hand, configuration (D) does not provide any bay redundancy but the provision of transfer bus and bus coupler increase the bay availability during the maintenance period of the circuit breaker. However, at a time only one bay can be transferred, as the transfer bus coupler is also responsible for the protection function of the transferred bay.

PART III – DISCUSSION OF THE RESULTS

The availability of all the configurations taken into consideration is calculated. The results of the percentage availability and the downtime are represented in Table 2 and Figure 7.

The first observation is that all of the numbers are very high, i.e. larger than 99.9%. This is rather expected since only the major faults were of interest. Major faults are not very common events; hence, the availability of the substation is very high in this sense. In practice, small faults are much more common, i.e. communication/control issues, but those do generally not affect the supply drastically and usually do not cause a power outage. A power outage is mainly caused by more severe faults, which do not happen that often in the switchgear.

Another aspect which makes the numbers so high is the total redundancy of supply being assumed. This kind of redundancy is common in some countries, but sometimes it is cost-effective to save funds by keeping redundancy lower than 100%. It mainly depends on the power utility and the country policies, as well as on the significance of continuous and reliable supply for the industry itself. However, full redundancy is still quite common, especially when further factory expansion is possible in the future.

Table 2: Summary of availability results

Configuration	Availability [%]	Down time [h/year]
(A)	99,92876014	6,241
(B)	99,92187796	6,843
(C)	99,99186321	0,713
(D)	99,91131071	7,769
(E)	99,97356661	2,316
(F)	99,99983795	0,014

The single busbar configuration (A) and the single busbar with section isolator (B) have availabilities around 99.92%, with latter one having a slightly smaller availability. This can be surprising at first glance, since it has an extra component, a section disconnecter. But this disconnecter will not improve the reliability value since it is an offload device and largely used for maintenance purposes. When it comes to the reliability, it is just another component that causes a power outage if it fails. It will, however, help with certain fault isolation, but summarized reliability effect will still be negative.

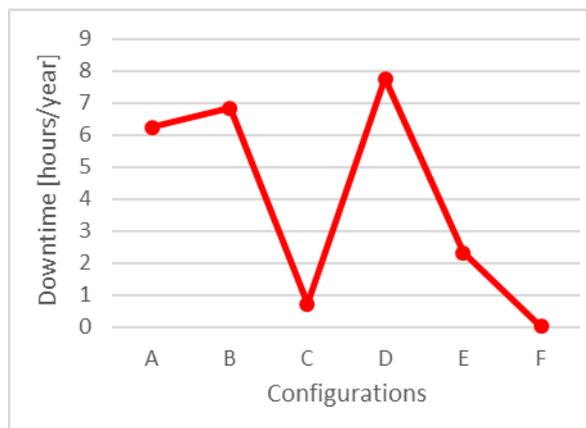


Figure 7: Summary of results

The single busbar with sectionalizer (C) has shown to be very reliable. By introducing a circuit breaker in the sectionalizing bay, the substation becomes much more reliable. This can be explained by the CB which can trip when the fault occurs in any of the corresponding sides of the busbar, hence isolating the fault from the healthy side without the supply being compromised. This possibility is useful, especially when substation consists of only two incoming lines, as in the evaluated example.

The one main and transfer configuration (D), on the other hand, shows poor reliability figures in comparison with other configurations, having the

lowest availability. It is due to the increased number of disconnectors. Furthermore, there is no parallel path to maintain the continuity of supply for each bay, like in (E) and (F). However, this type of system configuration is very useful to keep the supply during the maintenance of any equipment.

This can be achieved by corresponding disconnectors and transfer busbar. But when it comes to the general reliability of the configuration, its reliability is lower than other configurations, mainly due to a large number of disconnectors in the system, where each one of them will cause a total outage if it

fails. If a higher frequency of maintenance than usual is expected, e.g. due to salty water proximity, (D) could be taken more into consideration.

The last two configurations being evaluated are double busbar configurations. These configurations are much more complex and will, in general, improve the reliability of any system. But some interesting conclusions are visible here. Double busbar with single breaker (E) will reach a high availability, but still slightly lower than single busbar with sectionalizer (C). Hence, even with introducing a lot of redundancy, the total availability is lower. This happens since the increased number of components increases the chance of something failing, as well as increases maintenance time required for the substation in general. This effectively shows that sometimes introduction of more components and apparently, more redundancy does not guarantee a positive overall effect.

If the double breaker is introduced in the double busbar configuration (F), as the most complex configuration being evaluated, an extremely high reliability of supply to major faults is expected. This type of configuration has several CBs which can operate in the same principle as sectionalizing bay, providing a lot of redundancy. Any fault can be instantly isolated without affecting the supply. This is the only configuration which does not have a single component whose fail would cause an outage of the power supply, making it very reliable. It is important to notice that if more incoming lines and/or transformer bays were present, this type of configuration would most likely achieve an even larger positive effect compared to the other configurations.

PART IV – COST-BENEFIT ANALYSIS

Cost of equipment and cost of land are considered as investment costs. However, in practice, it also includes the cost of civil work, erection testing and commissioning, which also affects investment costs, but it varies during the execution. To estimate the cost of land, the switchyard layout was prepared using AutoCAD adhering to the clearances given in IEC 60071-1. The site altitude is assumed to be less than 1000 meter. The cost of land is taken from the summary of [6]. The average price of 75,000 SEK/hectare is considered for this project. By taking into consideration all the above, the following investment costs are derived for each of the configurations:

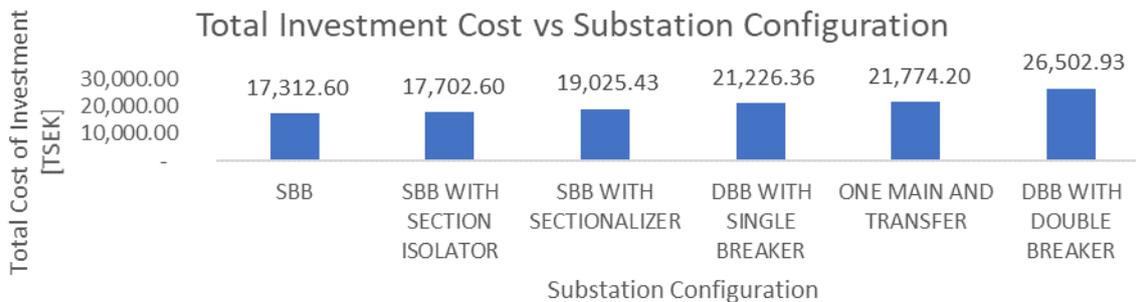


Figure 8: Total Investment Cost in TSEK, 1 TSEK=1000 SEK≈12,495.66 JPY≈110.33 USD≈96.95 EUR as on 02-11-2018

Figure 9 represents the relationship between the logarithm value of the unavailability of the configurations under consideration versus cost of initial investment.

SBB (A) has the lowest cost of investment but the downtime is high. Next configuration is SBB with section isolator (B). It has a slightly higher cost of investment compared to SBB but increased downtime. Therefore, if the decision making has to be made solely based on the overall availability of the substation, it is preferable to choose the SBB configuration (A) over SBB with the section isolator (B).

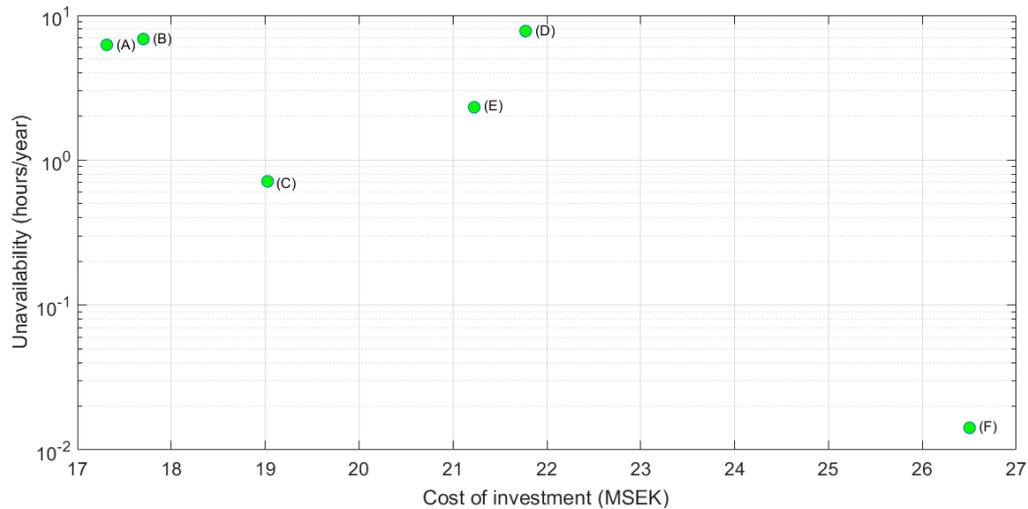


Figure 9: Unavailability vs Cost of investment, 1 MSEK = 1000 TSEK

SBB with a sectionalizer (C) has almost 10% higher investment cost than SBB (A), but it reduces the downtime considerably. Therefore, it can be further considered for the decision making. One main and transfer (D) and double busbar with single breaker (E) have almost 14.4% and 11.5% higher investment cost compared to the SBB with sectionalizer (C), respectively. However, the downtime with these configurations is higher than for the SBB with sectionalizer (C) and hence if the decision making has to be made solely based on the overall availability of the substation, it is preferable to opt for SBB with sectionalizer over these configurations.

DBB with double breaker (F) has a 39.3% and 53% higher cost of investment compared to SBB with sectionalizer (C) and SBB (A), respectively. It also has the lowest downtime amongst the configurations under consideration, therefore, it can be considered for the decision making. Based on this, (A), (C), and (F) are scrutinized.

Final selection should be made by taking the outage cost into consideration as well. Any power failure in a process plant will cause loss of revenue and sometimes loss of semi-finished product depending on the need of a continuous process. Restarting the production can also often be expensive and several hours long process. This can largely affect the profitability of the plant and hence, the final selection from the scrutinized configurations must be made after identifying and taking into consideration the total cost of an outage in a particular plant.

CONCLUSION

The substation configuration affects directly the cost of investment and the overall availability of the substation. Considering the financial dynamics and profitability, the industry can opt for investing more in the substation infrastructure initially, which will give long-term benefits by reducing the number and duration of outages. This paper illustrates the expected down-time of each configuration, while providing rough estimates of the corresponding investment costs. By optimizing this decision-making process, industry can avoid significant losses over the years. As the switching configurations remain the same for higher voltage levels, same analysis is applicable for EHV and UHV substations, for which the down-time is extremely important to reduce, as they often represent major nodes in the electric grid. The presented example and guidelines, together with information about a specific outage costs, can potentially help this decision-making process greatly.

AREAS OF FURTHER STUDY

1. It would be interesting to derive the life cycle model of the substation for various available switchgear technologies that also includes the yearly maintenance, residual cost at the end of the economic lifetime and the financial parameters like discounting and inflation rate. In this

paper costs for the maintenance were assumed to be similar and that their difference would not affect the presented study.

2. It is also assumed that the industry operates with 100% redundancy of the supply. However, it might not always be the case and hence, it might be interesting to study the effect of the reduced redundancy of the system.
3. There is a potential to develop an algorithm that provides the availability of more complex substation with a large number of bays using a machine learning and artificial intelligence platform.
4. For an application, specific to an industry, a detailed outage cost can be incorporated into the calculations, providing more detailed cost-benefit analysis.
5. Similar analysis can be done for configurations with larger number of incoming feeders, and it can be also expanded to the entire substation, i.e. including the outgoing MV switchgear.

BIBLIOGRAPHY

- [1] Joint Working Group, B3/C1/C2.14, "Circuit Configuration Optimization," CIGRE 585, 2014.
- [2] Working Group A3.06, "Final Report of the 2004 - 2007 International Enquiry on Reliability of High Voltage Part 2 - Reliability of High Voltage SF6 Circuit Breakers," CIGRE 510, 2012.
- [3] Working Group A3.06, "Final Report of the 2004 - 2007 International Enquiry on Reliability of High Voltage Equipment Part 3 - Disconnectors and Earthing Switches," CIGRE 511, 2012.
- [4] Working Group A3.06, "Final Report of the 2004 - 2007 International Enquiry on Reliability of High Voltage Equipment - Part 4: Instrument Transformers," CIGRE 512, 2012.
- [5] Canadian Electricity Association (CEA), "Forced Outage Performance of Transmission Equipment," CEA, 2017.
- [6] Statens Jordbruksverk, "Priser på jordbruksmark 2016," no. JO 38 SM 1701, 2016.