21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

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Reliable and Cost Effective Solutions for HVDC Switchyards

K. KUTLEV
ABB
USA

M. MAGNUSSON
ABB
Sweden

U. ANDERSSON
ABB
USA

SUMMARY

Most high voltage direct current (HVDC) converter stations, especially those based on classic thyristor valve technology, incorporate high voltage (HV) AC switchyards into the overall layout. Since HVDC applications typically transmit large amounts of bulk power with high availability and performance guarantees, the associated HV AC switchyards must be designed to meet high reliability and availability requirements. For these reasons, it is very important to select a switchyard fulfilling the requirements in a cost effective manner.

HV AC switchyards are generally implemented based on traditional bus configurations and equipment technologies. Selecting the most suitable configuration and technology can be a challenging task, since the most reliable switchyard configurations are typically associated with higher cost, although this is not always the case. Sometimes new technologies can be more reliable and cost effective.

Over the last 15 years, a new AIS technology has emerged, which can have significant positive impact on reliability and costs associated with each project. This is the Disconnecting Circuit Breaker (DCB) solution, which combines the functions of traditional circuit breaker and disconnect switch in a single unit. The DCB can also be combined with integrated Fiber Optic Current Sensor (FOCS).

The DCB technology requires less space, thus a smaller switchyard footprint, has lower operation and maintenance cost, provides improved safety and decreases project implementation time. In addition, the elimination of conventional AIS disconnect switches can lead to significant improvements in system reliability and availability.

This paper compares a "breaker-and-a-half' (BAAH) traditional AIS technology switchyard solution with a DCB (including FOCS) technology solution.

To find the most cost effective solution, the above mentioned switchyard alternatives are evaluated against different criteria, such as:

- Reliability of the power supply
- Initial investment cost
- Site acquisition and site preparation cost
- Operation and maintenance cost
- Cost related with poor reliability performance of the switchyard

krassimir.kutlev@us.abb.com.

Depending of the specific project requirements some criteria can have bigger impact than others. The Life Cycle Cost (LCC) for each alternative, considering the listed criteria, is then calculated based on an appropriate interest rate.

Based on the reliability and economic analysis, recommendations are then made for selecting the most reliable and cost effective, i.e., most optimal, AC switchyard solution.

KEYWORDS

Reliability, substation, disconnecting circuit breaker (DCB), fiber optic current sensor (FOCS), life cycle cost (LCC).

1. INTRODUCTION

Most high voltage direct current (HVDC) converter stations, especially those based on classic thyristor valve technology, incorporate high voltage (HV) switchyards into the overall layout.
These HV switchyards allow for more flexible connections with:

- HVDC converter transformers
- AC filter and shunt capacitor banks (required for thyristor valve based HVDC applications)
- AC network connections, including local generators (if applicable)

Since HVDC applications typically transmit large amounts of bulk power with high availability and performance guarantees, the associated HV switchyards must be designed to meet the high reliability and availability requirements. For abovementioned reasons, it is very important to select a switchyard fulfilling these requirements in a cost effective way.

The purpose of this paper is to show one approach to select the most cost effective HV switchyard based on reliability and economics evaluation.

2. SELECTING HV SWITCHYARD ALTERNATIVES

The HV switchyard can be implemented with different configurations and technologies. Each technology has specific advantages and disadvantages. Selecting the most suitable configuration and technology can be a challenging task. Typically, the most reliable switchyard solutions are more expensive, although this is not always true. Sometimes a new technology can be more reliable and more cost effective. The goal in this paper is to show a methodology for selecting the most cost effective and reliable AC switchyard that fulfills the specific requirements for HVDC systems.

In general, the AC switchyards are built with traditional Air Insulated Switchgear (AIS) technology. Depending of the specific requirements, different configurations are used, such as Double Bus Double Breaker (DBDB), Double Bus Single Breaker (DBSB), "H" configuration, Breaker and a Half (BAAH), Ring Bus, etc. The selection of any of these solutions depends of the required level of reliability and the specifics for each project. In addition, during the last 15 years, new AIS and Gas Insulated Switchgear (GIS) technologies has emerged in the substation market. These technologies can have significant positive impact on reliability and cost associated with each substation project. One emerging technology is the Disconnecting Circuit Breaker (DCB) solution, which is combining the functions of traditional circuit breaker and disconnect switch in a single unit. The DCB can also be combined with integrated Fiber Optic Current Sensor (FOCS). The DCB technology requires less space, thus a smaller switchyard footprint, has lower operation and maintenance cost, provides improved safety and decreases project implementation time. In addition, the elimination of conventional AIS disconnect switches can lead to significant improvements in system reliability and availability. This is especially true, when the switchyard is located in harsh environment conditions, such as polluted air, wind and dust, rain and snow.

The following options for potential HV configurations for HVDC systems implemented with different technologies are subject for this paper:

- Option 1 - Double Bus Double Breaker (DBDB) configuration implemented with traditional AIS technology
- Option 2 - Breaker And A Half (BAAH) configuration implemented with traditional AIS technology
- Option 3 - Breaker And A Half (BAAH) configuration implemented with Disconnect Circuit Breaker (DCB) technology

Each of the proposed HV switchyard alternatives will be modeled and evaluated from reliability and economic point of view.

3. RELIABLITY CALCULATIONS AND ANALYSIS

An ABB specialized software for reliability modeling and analysis of substations called SubRel™ is used for this paper. SubRel™ uses a dynamic state enumeration method for substation reliability assessment. To do this, SubRel™ models every possible contingency, determines the impact of each contingency, determines the frequency of each contingency, and sums up the impact of all contingencies for an overall reliability assessment. The end result is the expected number of annual interruptions and the expected number of annual interruption minutes for each component in the system. The software is considered that the protection system is perfect, i.e., when a fault occurs the faulted equipment is always isolated. Description of the symbols used in SubRel™ tool are show in Table 1.

Reliability data from open sources as CIGRE and CEA [1-4] are used to build reliability model for the proposed options. For each of the options there are five incoming feeders, shown as a source of power and six outgoing feeders, shown as loads.

- Circuit Breaker	- Voltage Transformer
- Disconnecting Circuit Breaker	- Source of Power
- Disconnect Switch	- Load
- Current Transformer / FOCS	- Clamp
- Ground Switch	

Table 1. Symbols used in SubRel™ single line diagram (SLD)

Figure 1 shows reliability model for Option 1 - DBDB configuration implemented with traditional AIS technology. This option is implemented with 22 live tank circuit breakers (LTB) and it is typical for substation applications in Europe and in oil and gas facilities around the globe. In general, this configuration is reliable and flexible but requires significant initial investments.

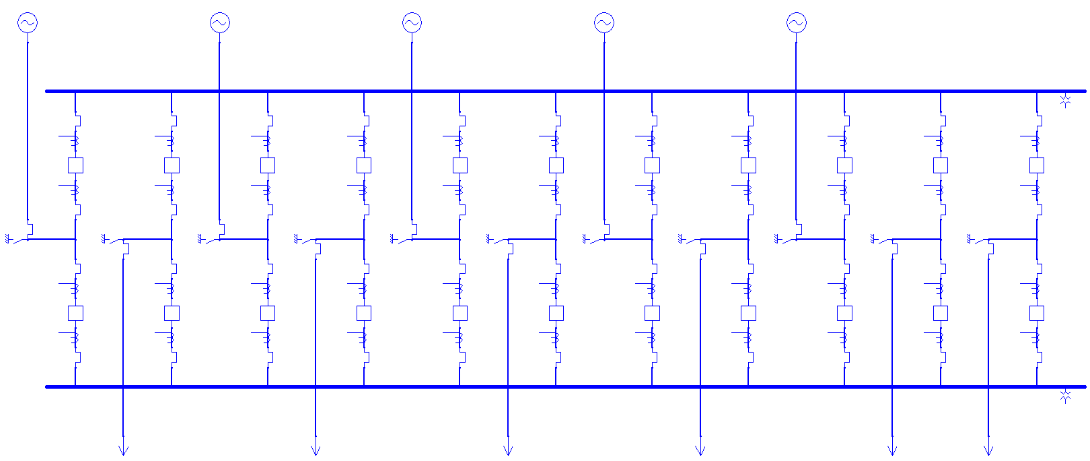

Figure 1. DBDB configuration with traditional AIS technology

Figure 2 shows reliability model for Option 2 - BAAH configuration implemented with traditional AIS technology. This option is implemented with 17 LTB circuit breakers, it is typical for the North American market and getting more popular around the globe. It has five circuit breakers less than DBDB configuration and as such, will require less initial investments.

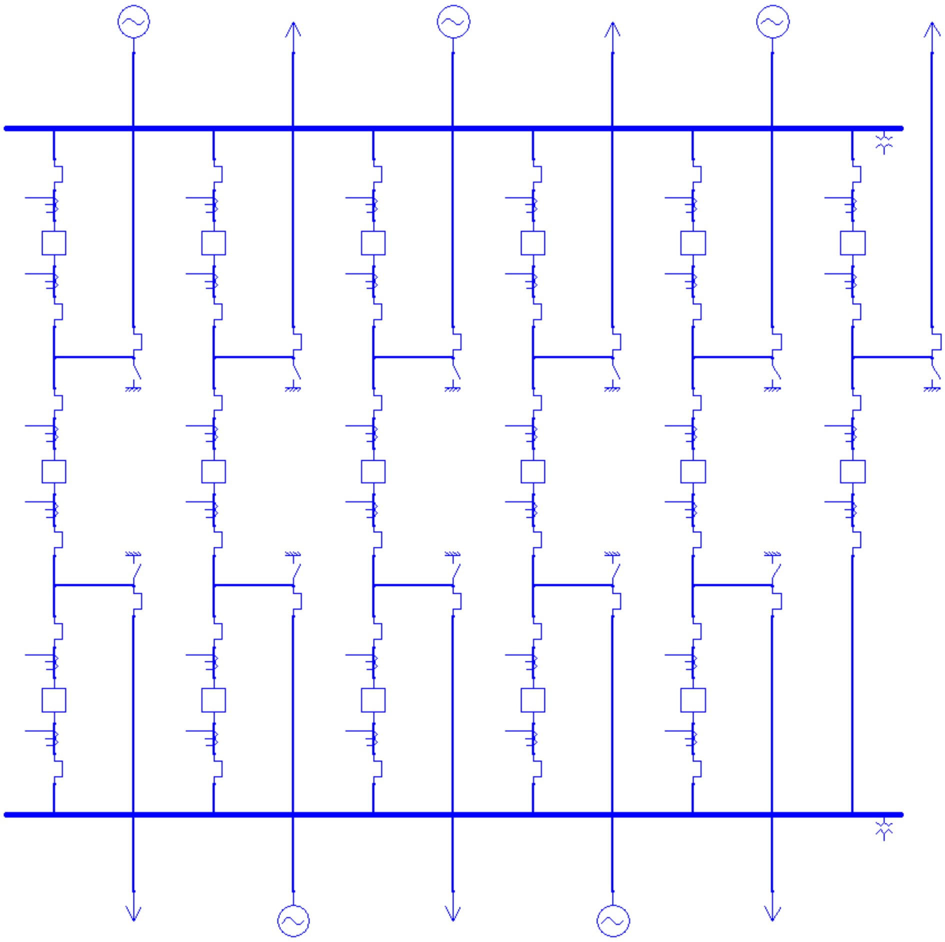

Figure 2. BAAH configuration with traditional AIS technology

Figure 3 shows reliability model for Option 3 - BAAH configuration implemented with DCB technology. This switchyard alternative uses the same number of circuit breakers as Option 2 but without two disconnect switches around each breaker. Integrated fiber optic current sensor (FOCS) are also used instead of the traditional current transformers (Figure 4).

The DCB is designed in accordance with its own IEC 62271-108 standard [5], which refers to both, the circuit breaker standard IEC 62271-100 [6] and the disconnect and ground switch standard IEC 62271-102 [7]. The DCB standard also includes requirements on more extensive testing on the indication system, interlocking system and dielectric withstand. Improved reliability and availability is expected with this relatively new technology, due to the less equipment and high reliability for the disconnecting operations in SF_6 gas environments.

Disconnect clamps are used around each of the DCB. These clamps can be removed when repairing or maintenance is required for the DCB. To do that, both clamps should be isolated before. After opening the clamps, the power can be easily restored for the rest of the switchyard. This leads to significant improvements in reliability and availability for this configuration.

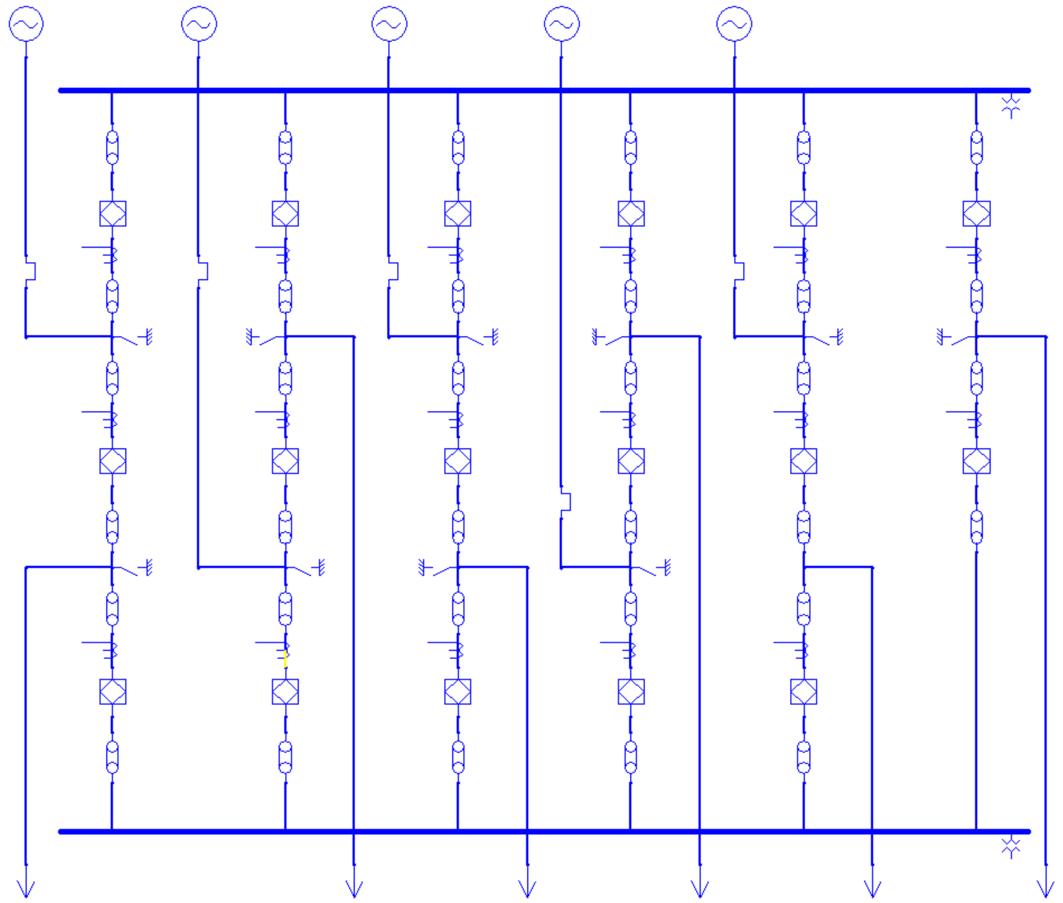

Figure 3. BAAH configuration with DCB and FOCS technology

The FOCS is designed as a redundant 3-phase sensor system consisting of two optoelectronic (OE) modules, three sensor heads, and the fiber cables in between (Figure 4). The OE module houses the optoelectronics to transmit and receive the signal to the fiber coils (3 phases). One sensor head is integrated in each phase of the disconnecting circuit breaker unit. Each sensor head contains two fiber coils in order to enable redundancy on the system level. Since the FOCS sensor head is a passive component and the OE is placed in cubical on ground level potential outages are minimized. Maintenance and replacements without outages in the main HV circuit can be achieved due to the redundant design with “hot swappable” electronics.

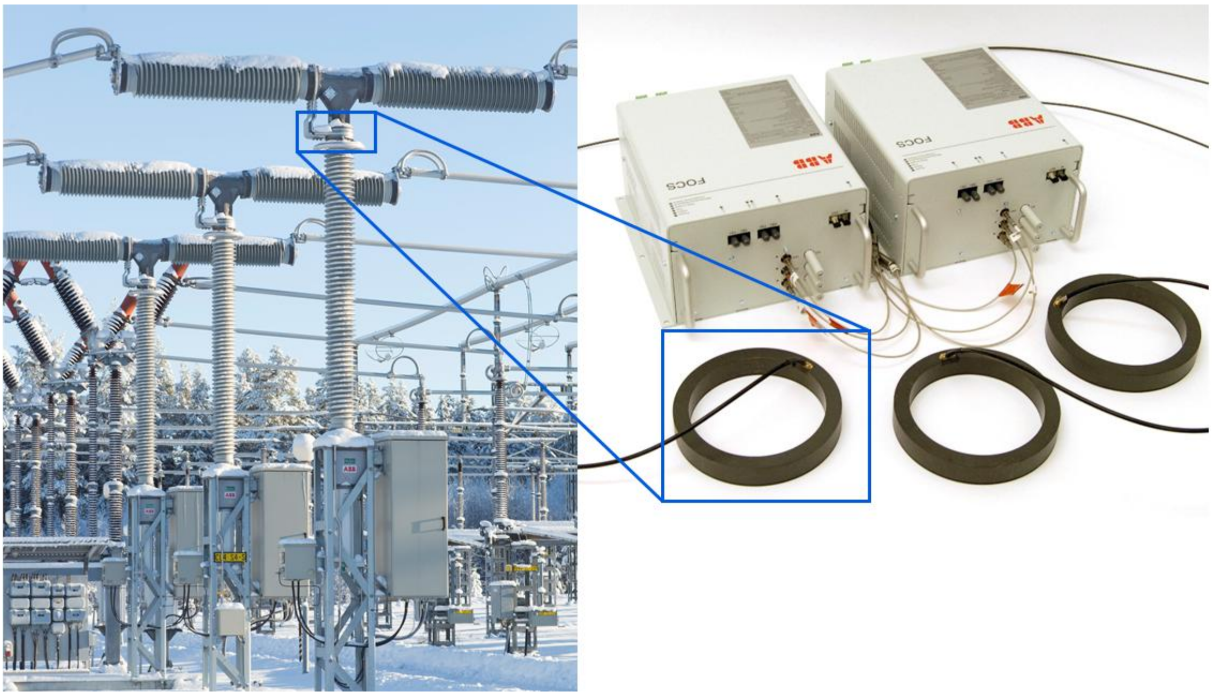

Figure 4: Three-phase FOCS kit to the right including three sensor heads and two optoelectronic modules (redundant). The location of the FOCS sensor head in the DCB is shown to the left.

Reliability results for all six outgoing feeders are calculated for each option. Table 2 shows the following reliability results:

- **Failure OF (FOF) –** Outage frequency related to the probability of equipment fault during the normal and maintenance operating states, /yr
- **Maintenance Outage Frequency (MOF)** – Outage frequency related to the equipment maintenance, /yr
- **Total Outage Frequency (TOF) –** The total number of times per year when the piece of equipment will be out of service – TOF = Failure OF + Maintenance OF, /yr
- **Failure Outage Duration (FOD)** – Outage duration related to the equipment fault during the normal and maintenance operating states, hr/yr
- **Maintenance Outage Duration (MOD)** – Outage duration related to the equipment maintenance, hr/yr
- **Total Outage Duration (TOD)** – The total number of hours that the piece of equipment will be de-energized in a typical year – TOD = Forced OD + Maintenance OD, hr/yr
- **Mean Time Between Failure (MTBF)** – Mean time between two failure outages, i.e., 1/FOF, yr

Configuration	Feeder Name	Failure OF /yr	Maint. OF /yr	Total OF /yr	Failure OD hr/yr	Maint. OD hr/yr	Total OD hr/yr	Forced MTBF yr
Option 1 **DBDB with traditional AIS**	Load T1	0.2455678	0.600	0.8455679	0.25272	4.800	5.05272	4.07
	Load T2	0.2455678	0.600	0.8455679	0.25272	4.800	5.05272	4.07
	Load T3	0.2455678	0.600	0.8455679	0.25272	4.800	5.05272	4.07
	Load T4	0.2455678	0.600	0.8455679	0.25272	4.800	5.05272	4.07
	Load T5	0.2455678	0.600	0.8455679	0.25272	4.800	5.05272	4.07
	Load T6	0.2455678	0.600	0.8455679	0.25272	4.800	5.05272	4.07
Option 2 **BAAH with traditional AIS**	Load T1	0.2459218	0.600	0.8459218	0.25324	4.800	5.05324	4.07
	Load T2	0.2459218	0.600	0.8459218	0.25324	4.800	5.05324	4.07
	Load T3	0.2459386	0.600	0.8459386	0.25325	4.800	5.05325	4.07
	Load T4	0.2459846	0.600	0.8459846	0.25328	4.800	5.05328	4.07
	Load T5	0.2459386	0.600	0.8459386	0.25325	4.800	5.05325	4.07
	Load T6	0.2459218	0.600	0.8459218	0.25324	4.800	5.05324	4.07
Option 3 **BAAH with DCB technology**	Load T1	0.0249000	0.133	0.1583444	0.05950	0.267	0.32631	40.16
	Load T2	0.0257709	0.133	0.1591709	0.06110	0.267	0.32790	38.80
	Load T3	0.0249000	0.133	0.1583402	0.05940	0.267	0.32624	40.16
	Load T4	0.0258000	0.133	0.1591692	0.06110	0.267	0.32790	38.76
	Load T5	0.0258000	0.133	0.1591695	0.06110	0.267	0.32790	38.76
	Load T6	0.0233000	0.133	0.1567467	0.04670	0.267	0.31349	42.92

Table 2. Reliability results

The following conclusions can be made regarding reliability of each configuration:

- The DBDB and BAAH switchyards implemented with the same technology (traditional AIS) have the same level of reliability. Thus, if the level of reliability is dominant for building the switchyard, BAAH configuration will be definitely a more cost effective solution with five circuit breakers less. Both configurations have practically the same outage frequency, outage duration and mean time between failure.
- Option 3, BAAH configuration implemented with DCB technology has the best reliability numbers.
  - The mean time between failure is from 39 to 40 years versus 4.1 years for Options 1 & Option 2.
  - The outage frequency due to equipment maintenance is impacted only by the time for isolating and removing the clamps and is 4.5 times lower.
  - The total outage frequency is 5.3 times lower
  - The failure outage duration is in average 0.06-0.061 hours per year versus 0.253 hours per year for Options 1 and 2.
  - The DCB Option 3 also has less outage duration when the piece of equipment is maintained due to the clamps used in this configuration.
  - Overall the total outage duration for a load feeder in DCB alternative is 15.4 times lower.

4. LIFE CYCLE COST ANALYSIS

For more precise evaluation of the proposed three options, the life cycle costs are considered for each of them. The LCC includes the following ingredients:

- Capital investments cost
- Land acquisition and site preparation cost
- Operation and maintenance cost
- Cost of power interruption

All of the cost above are combined in the switchyard total LCC with interest rate of 5% and for thirty years period of time.

The reliability results for the three switchyard options show that the DBDB and BAAH configurations implemented with traditional AIS technology have the same level of reliability. Since the DBDB configuration requires five more circuit breakers, it is clear that this option is not competitive from economic point of view. Therefore, in the life cycle cost, comparisons are consider only for Options 2 and Option 3.

There are several advantages of using the new DCB technology in comparison to the traditional one:

- Improved reliability by avoiding the air insulated disconnect switches
- Smaller footprint and all of the benefits related to that – less cost for site acquisition and preparation, reduced needs for foundations, steel, and cable trenches.
- Lower operational and maintenance (O&M) and outages cost – DCB switchyard requires less maintenance work at site. As results, it will be savings in direct maintenance cost as well as in the costs related to maintenance related outages.

Figure 5 shows a typical switchyard with traditional AIS technology, including disconnect switches, LTB circuit breakers, and current transformers.

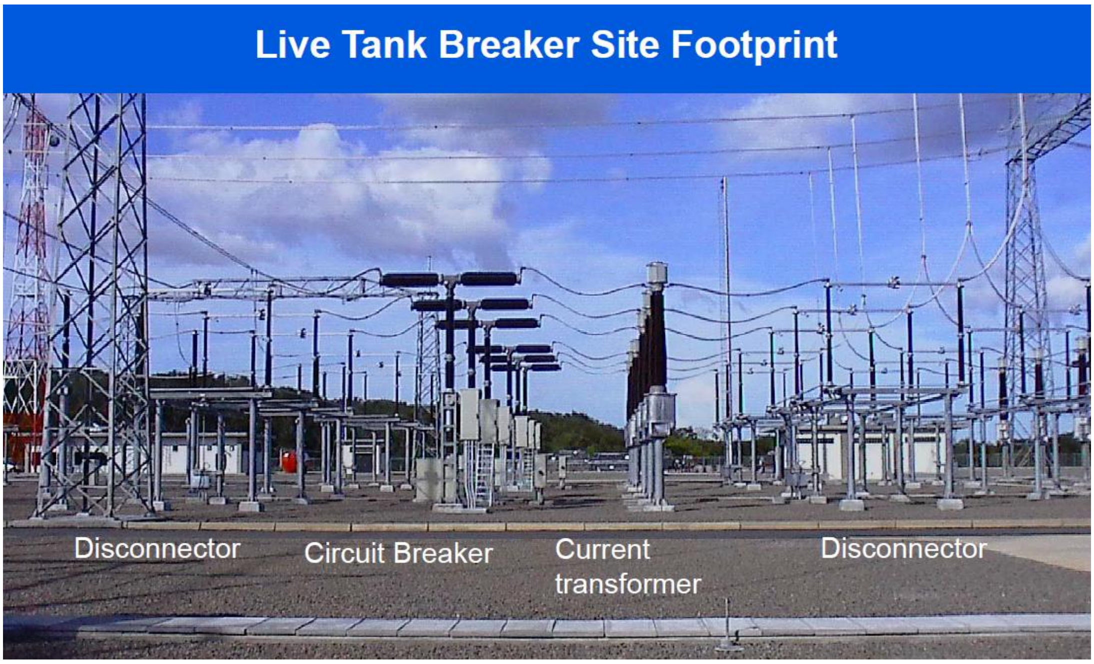

Figure 5. HV switchyard with traditional AIS technology

Figure 6 illustrate the space saving that will be achieved for the same switchyard site, when the DCB technology is used together with integrated FOCS. As result, for our 345 kV switchyard the total footprint for the substation will be reduced from 36,285 m^2 to 22,463 m^2, resulting in a 38% reduction.

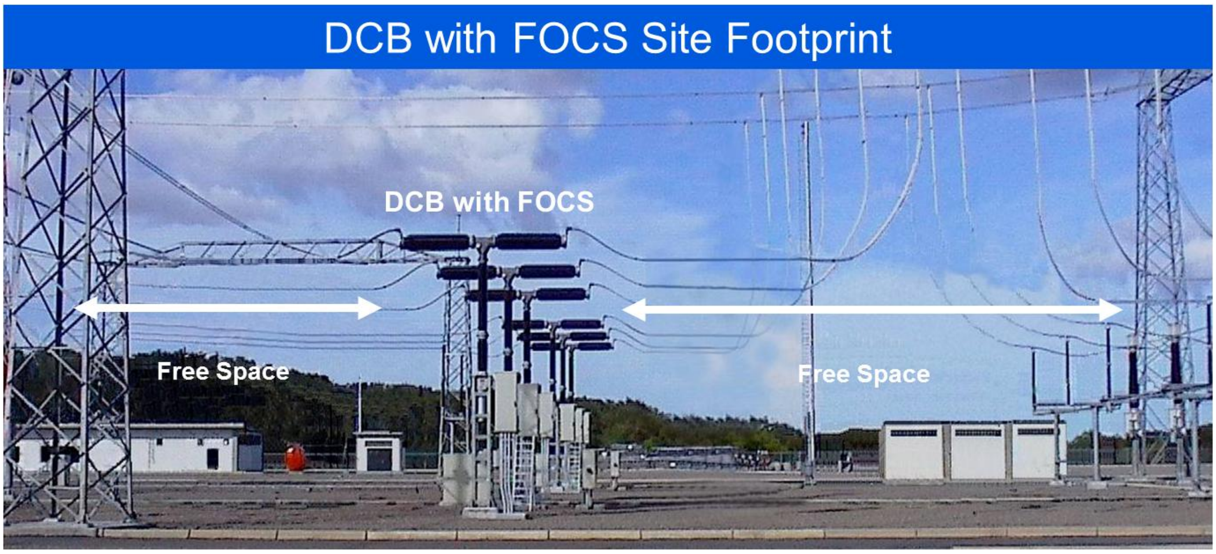

Figure 6. HV switchyard with DCB technology and FOCS sensors

To compare both switchyard options, with traditional AIS technology and with DCB technology, we calculated the total life cycle cost for each of them. The LCC include the initial capital cost, site acquisition and preparation cost, operation and maintenance cost, cost of power interruption [8], all of them calculated for 30 years project life with 5% interest rate. The graphical presentation of the LCC and its ingredients for each option are shown in Figure 6.

The investment costs, which include the initial capital cost and site acquisition and preparation cost are with 2.6 MUSD (8.7%) higher for the switchyard with traditional AIS technology. The DCB technology option has 0.512 MUSD (67%) lower O&M cost for the 30 years period. In addition, the cost of interruption for DCB alternative are with 5.28 MUSD (over 8 times) less. Overall, the alternative with DCB technology will have 8.4 MUSD (26.8%) less life cycle cost in comparison to the alternative implemented with traditional AIS technology.

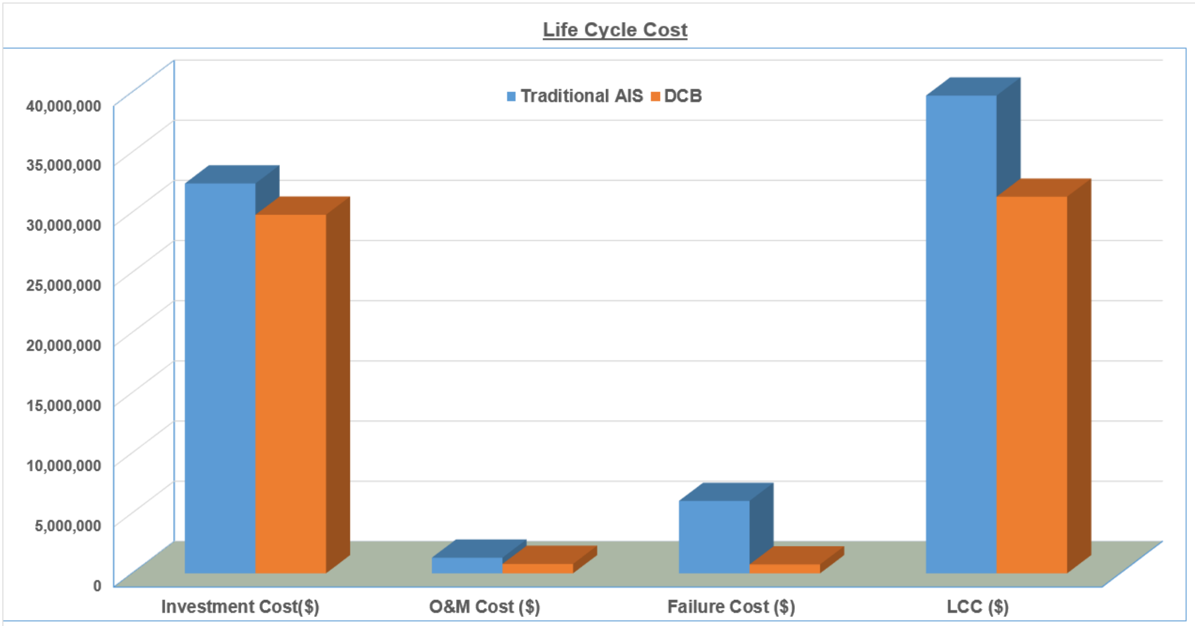

Figure 6. Life Cycle Cost comparison for Options 2 - traditional AIS and Option 3 - DCB with FOCS

5. CONCLUSSION

In order to select the most cost effective HV switchyard in HVDC system, we have to evaluate each of the proposed alternatives from:

- Reliability – by modeling each of the proposed switchyard alternatives and calculating their reliability
- Economic – by calculating the initial investment, O&M cost, and cost of power interruption, all of them combined for the life cycle of the project with the suggested interest rate.

Following this methodology will allow us to identify the most reliable switchyard alternative and to identify the most cost effective solution. In this case, the most reliable switchyard alternative is also the most cost effective. This approach allows us to justify which HV switchyard alternative for HVDC system should be selected based on its reliability and associated life cycle costs.

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