Losses and cost comparison of DS-HB and SD-FB MMC based large utility grade STATCOM

Georgios Tsolaridis[1], Heverton A. Pereira[2], Allan F. Cupertino[3], Remus Teodorescu[1], Massimo Bongiorno[4]

[1] Department of Energy Technology, Aalborg University, Aalborg, Denmark
[2] Department of Electrical Engineering, Federal University of Viçosa, Viçosa, Brazil
[3] Department of Materials Engineering, Federal Center for Technological Education of Minas Gerais, Belo Horizonte, Brazil
[4] Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden

***Abstract*— Among the various multilevel converter topologies used in medium and high voltage grid applications, the Modular Multilevel Converter (MMC) has been the most promising since it combines good harmonic performance with low switching frequency and high reliability. A major concern however for inverter designers has been the associated cost due to the need for a large number of power devices and capacitors.**

This paper focuses on the application of MMC in transformer-less STATic synchronous COMpensators (STATCOMs). Initially, the double-star half bridge (DS-HB) and the single-delta full bridge (SD-FB) configurations are presented. Their specific components are designed in an analytical way followed by loss estimation. Finally, a comparison of the necessary components gives an insight of the total cost associated with each configuration.

Keywords*— *MMC STATCOM, HVDC, losses analysis, cost comparison

I. Introduction

Medium voltage and high voltage grid applications require the use of power devices with high blocking voltage capability. However high power devices are not commercially available for voltage ratings higher than 6.5 kV [1]. One possible solution would be the use of a transformer connected to the output of the inverter. These transformers are usually expensive and bulky, increasing significantly the cost of the system [1]. Consequently, multilevel topologies appear as the most promising solution for grid applications.

Among the various multilevel topologies that have been researched, the Modular Multilevel Converter (MMC) is considered as the next generation converter for medium and high voltage grid STATCOM applications. It combines excellent harmonic performance and low switching frequency with high reliability and design flexibility. In addition, high power quality is a major concern nowadays with the grid codes requiring efficient control of both positive-sequence and negative-sequence reactive power. In particular, the control of negative sequence reactive power is a crucial power quality requirement when non-linear loads, like arc furnaces, are present.

The MMC family is usually classified into four different configurations, described thoroughly in [2]:

- Single-Star Full Bridge (SS-FB);
- Single-Delta Full Bridge (SD-FB);
- Double-Star Half Bridge (DS-HB);
- Double-Star Bridge Cells (DS-FB).

The SS-FB configuration's ability to control negative-sequence reactive current is limited by the voltage rating of the converter, since it requires the injection of a zero-sequence voltage equal to the phase voltage [3]. This need for overdesigning the voltage rating by a factor of two makes it unsuitable for modern STATCOM applications. In addition, the DS-FB, despite its superiority over the other configurations, is usually not recommended due to the large number of power devices needed and its low practicability [1]. On the other hand, the SD-FB and the DS-HB appear as very attractive solutions for STATCOM applications due to their ability to control both positive and negative sequence reactive power in a large operating range [2].

In this paper, the SD-FB and DS-FB configurations will be initially presented and their components will be analytically designed for a STATCOM application that is able to control *1 pu* negative-sequence reactive power. A loss calculation will follow, based on the power device manufacturer's datasheets. Finally, a comparison of the necessary components and the associated capital and operational expenditures will take place. The final purpose of this work is to point at the preferred MMC configuration choice for large utility grade STATCOM applications.

II. MMC Configurations

The SD-FB configuration in a STATCOM application was evaluated in [4]. The complete circuit configuration is shown in Fig. 1, where the MMC is connected through the inductors L_{ac} to the three-phase grid. Multiple single-phase H-bridge cells are cascaded to form a branch. The three branches are connected in a delta configuration through the coupled inductors L_{CM}. As mentioned in the introduction, one advantage of this configuration is that the circulating current can be used to allow energy exchange between the phase legs and thereby can be used under unbalanced conditions. However, this configuration can only control the full negative sequence reactive power (*1pu*) when it is designed for a current rating of *2 pu*, since a zero-sequence component current equal to the negative sequence injected current, needs to circulated between the delta connected branches [5].

Fig. 2 depicts the DS-HB configuration in a STATCOM application. In this case, multiple bidirectional chopper cells, are cascaded to form a converter arm. The upper and lower arms of each phase are connected through two arm inductors to the PCC. The performance of this topology was evaluated in [2]. As in the SD-FB configuration, the presence of the circulating current makes the DS-HB configuration very attractive for STATCOM applications. Furthermore, in contrast to the SD-FB, the DS-HB can be used to control the full negative-sequence reactive power (*1pu*) without increasing the conduction losses of the system and without the need to over-design the converter's components. The circulating current between the converter legs for this configuration is negligible in comparison to the negative sequence current that is injected. Thus, the total arm current is not a function of the negative sequence current as in the SD-FB topology.

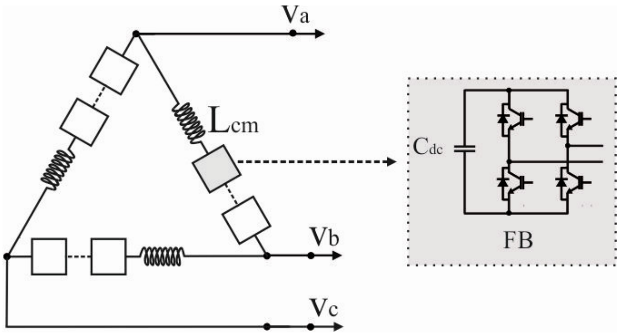

Figure 1: Single Delta – Full Bridge STATCOM configuration

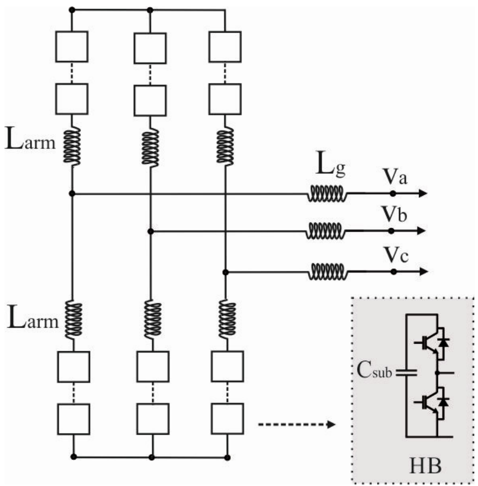

Figure 2: Double Star – Half Bridge STATCOM configuration

III. Topologies Design

A. Number of submodules

Although in both studied topologies, no physical dc-link is present, the methodology used in traditional 2L-VSC can be adapted. The necessary effective dc-bus voltage is calculated and it is divided by the submodule's (SM) capacitor voltage, obtaining the number of SM per arm/branch.

The calculation of the minimum dc-bus voltage is based on the following points [1]:

- Output impedance of STATCOM is considered 8 % with a variation of 5 % around this value;
- Grid voltage can change 5 %;
- DC-bus voltage presents in the worst case 10 % of ripple and a constant error of 3 % in steady-state.

Based on these assumptions, the maximum voltage synthetized by the STATCOM is given by:

(1)

where is the line voltage synthetized by the STATCOM and is the PCC line voltage. Considering a modulation factor equal to 1.104 [1], for delta topology:

(2)

where is the maximum modulation index of the converter. For Double-Star topology, the maximum modulation index is defined as:

(3)

Considering the IGBT's switching frequency equal to 360 Hz and for the minimum on-time and dead-time, it is possible to obtain a maximum modulation index of . Therefore, the dc-voltage necessary for each topology is:

(4)

. (5)

An Infineon IGBT part number (FF600R17) of 1.7kV-600A, is chosen for this application. The operating voltage is chosen to be 0.9kV [6], and 10% of SM redundancy is added [7]. Thus, the number of SM per branch in Delta topology is:

, (6)

and the number of SM per arm in Double-Star topology is:

. (7)

B. Capacitor design

The cell capacitance selection is a trade-off between sub-module voltage requirements and capacitor size. The total cell capacitance is generally defined between 30−45 kJ per MVA of converter, and a methodology to calculate the capacitance value, based on energy storage requirements is presented in [8].

For delta topology, the methodology proposed by [1] is used. The dc bus voltage ripple becomes maximum when a purely reactive current flows. Therefore:

(8)

where is the RMS value of the ac voltage per submodule and is the RMS current. This way, the submodule capacitance can be calculated by:

(9)

Considering the converter's parameters shown in Table I, the SM capacitor value in Delta topology is. For Double-Star topology, reference [6] proposes a methodology based on minimum storage energy requirements. Thus, the submodule capacitance can be determined by:

(10)

where is the nominal energy storage per arm.

Considering the system injecting nominal reactive power into the grid with the maximum modulation index, the required nominal energy storage in the converter per transferred VA is approximately, 42 kJ/MVA [8]. This way, the nominal energy storage by arm is given by:

(3)

Using this value of nominal energy storage by arm, the necessary capacitance per submodule is found to be .

C. *Inductor design*

In MMC topologies, inductors are placed in the converter arms to suppress transients in the circulating [9] and limit fault currents [10]. For grid-connected applications, suitable values of the arm inductors could very well be in the range of 0.1 p.u. In DS-HB topology a value of 28 % for the arm inductor is chosen, as used in [8]. In SD-FB topology, a common mode inductor of 37 % is used while the ac link inductor is 8 % [4].

IV. Losses Analysis

At this point, an estimation of the switching losses will be made for the configurations that were designed in the previous sections. The devices are considered to be operating with a junction temperature of 125˚C. The gate resistance is considered to be 1 Ω and the gate bias is ±15 V.

The loss estimation is based on a simple model that takes into account the instantaneous current flowing through the submodule and data found in the device datasheet, as shown in Fig. 3. It should be noted that in the case of the SD-FB, unipolar PWM is considered.

The IGBT's voltage drop as well as the diode's forward voltage drop is expressed as a function of the current, resulting in the total conduction losses of each cell as shown in Fig. 3. Similarly, the turn on and turn off along with the reverse recovery energy losses are expressed as a function of the current, resulting in the switching losses of the IGBT and diode respectively [6]. Due to the symmetry ensured by PS-PWM, the result can be extended for all the submodules. The current is considered to be sinusoidal, leading 90˚ the phase voltage.

TABLE I. SPECIFICATIONS OF MMC INVERTER

	Topologies		
	Description	***DS-HB***[a]	***SD-FB***[b]
N	Number of SM	79 (\arm)	68 (\branch)
C_{dc}	SM capacitance (mF)	26.2	38.5
L_{arm}	Arm inductor	9.7 mH (28%[a])	-
L_{cm}	Common mode inductor	-	6.4 mH (37% [b])
L_g	AC-link inductor	-	1.4 mH (8% [b])
S	Rated power (MVA)	100	200
V_{SM}	Sub-module voltage (kV)	0.9	0.9
f_{sw}	Switching frequency (Hz)	360	360
f	Grid frequency (Hz)	50	50
f_{swe}	Effective switching frequency (kHz)	56.88	48.96
V_{grid}	Grid voltage (kV)	33	33
I_g	Injected nominal current	1750	3500
I_{SM}	SM RMS current (A)	875	2020
IGBT	IGBT in parallel	2	4

a.[a] 33kV, 100MVA, and 50-Hz base; [b] 33kV, 200MVA, and 50-Hz base;

b.

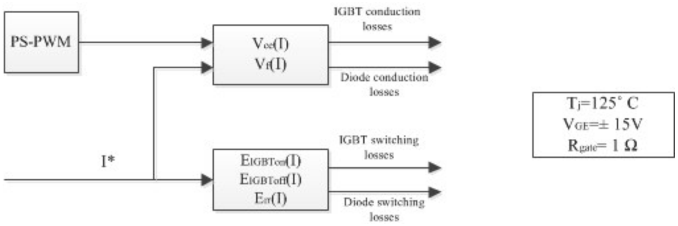

Figure 3: Model Based Loss Estimation

The switching losses depend on the operating conditions and the amount of negative sequence current injection. As noted before, the DS-HB uses a small amount of DC circulating current in order to control the negative sequence current. This means that in all cases, *1 pu* power is translated into *1 pu* current for the DS-HB configuration. On the other hand, the SD-FB configuration requires the injection of a zero sequence component equal to the amount of negative sequence current [5], increasing the switching losses. Table II depicts the losses when *1 pu* positive sequence reactive power is exchanged with the grid.

TABLE II. Loss Comparison for *1pu* Positive Sequence Injection

	Conduction Losses (kW)	***Switching Losses (kW)***	***Total Losses (kW)***
DS-HB	750.8	141.6	892.4
SD-FB	782.9	272.1	1055

Table II shows that even when no negative sequence current is exchanged, the efficiency of the DS-HB configuration is slightly higher (99.11% instead of 98.96%) than the SD-FB. This is however normal since the SD-FB converter was overdesigned by a factor of two in order to be able to control full negative sequence reactive power.

Fig. 4 breaks down the losses into IGBT and diode losses for the two configurations. The conduction losses are similar in both cases, but due to the higher number of IGBT and diode parts, the amount of the devices that switch is higher in the SD-FB configuration, leading to higher switching losses.

Figure 4: Losses of IGBT and Diode comparison for 1 pu positive sequence reactive power injection.

In Fig. 5 the switching losses of the two compared topologies are shown as a function of the negative sequence reactive power , respecting always that the total exchanged reactive power is: , with being the positive sequence reactive power.

As can be deduced by Fig. 5, the total losses in the case of the DS-HB are independent of the amount of exchanged negative sequence reactive power, due to the negligible circulating current that is needed in order to keep each phase balanced. On the other hand, the total current needed in the SD-FB is increasing linearly with the increase of the negative sequence reactive power. As a result, the conduction losses increase, reducing the efficiency of the converter system. Particularly in the case of 1 pu negative sequence reactive power, the efficiency of the SD-FB configuration drops to approximately 98%. It should be noted that this analysis accounts only for the losses of the switches and does not take into consideration the losses on the arm inductors, which are considered to be ideal.

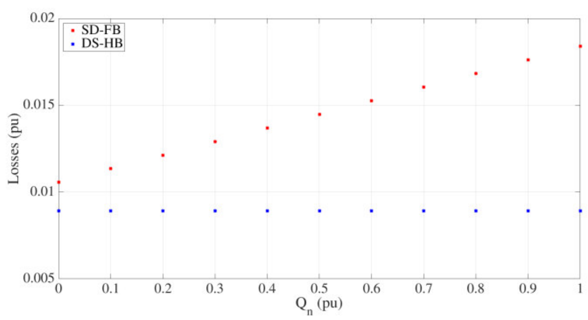

Figure 5: Loss Comparison as a function of .

Concluding the loss analysis section, Table III depicts the losses when *1 pu* negative sequence reactive power is exchanged with the grid. As expected the high current results in almost double losses for the SD-FB configuration.

TABLE III. Loss Comparison for full Negative sequence injection

	Conduction Losses (kW)	***Switching Losses (kW)***	***Total Losses (kW)***
DS-HB	750.8	141.6	892.4
SD-FB	1596	285.6	1881.6

V. Cost Analysis

In this section, an estimation of the total cost of the two compared configuration will take place. The total cost will be broken down to capital expenditure (CAPEX) and operational expenditure (OPEX). The initial cost is based on the number of components required and the price per part number. For the current analysis the cost of the power electronic modules as well as the price of the capacitor banks will be considered, since all the other components are considered to account only for a small percentage of the total cost.

An overview of the most important components that each configuration utilizes is shown in Table IV. The DS-HB requires less power modules but on the other hand has greater energy storage requirements. For the completeness of the analysis, the number of gate driver units, current sensors and voltage sensors is also included, although these components only account for a minor part of the total cost.

For a more detailed evaluation of the cost, the capacitors have to be chosen carefully for each configuration. As pointed out in the section III.B, the two configurations were designed with low cost power modules. This choice however has led to large energy storage requirements, making the capacitor cost dominant. It should be clarified that in this paper *1 unit* is equivalent to *1000 £*. From now on, all costs will be measured in units.

TABLE IV. SPECIFICATIONS OF MMC INVERTER

Component	**Quantity**	
	DS-HB	***SD-FB***
IGBT	1896	3264
Gate Drive Unit	948	816
Capacitor [kJ]	4200	3183
Current Sensor	6	3
Voltage Sensor	3	3

Aluminum Electrolytic Capacitors are chosen for this application [11]. The rated voltage of the chosen capacitors is *500 V* so two of them need to be connected in series. The resulting capacitance drops then to *3.4 mF*. For the DS-HB configuration 16 capacitors are required per submodule while for the SD-HB configuration 22 of these capacitors are required per submodule. The initial cost per submodule is then normalized and calculated as shown in Table V.

TABLE V. Cost per Submodule

Component	Quantity	
	DS-HB	***SD-FB***
Module Cost (units)	0.48	1.92
Capacitor Cost (units)	1.4	1.93
Total Cost (units)	**1.88**	**2.85**

In the case of the SD-FB, it is worth noting that the development cost of one submodule is shared equally between the cost for the power module and the capacitors, despite the fact that low cost power modules were used. On the other hand, in the DS-HB configuration, the capacitor cost is by far the dominant one.

Fig. 6 gives an insight of the capital expenditure of the two configurations as well as the cost distribution between the power module and the capacitors for each case. It is very interesting to notice that the DS-HB configuration despite the significantly lower power device cost, resulted in approximately 14% higher CAPEX due to the high energy storage requirements that account for 75% of its CAPEX.

The operational cost, especially for large utility grade applications, is significant. The analysis of the operational cost (OPEX) will be based on the cost per kilowatt-hour along with the operational losses. In the case of the DS-HB the operational cost is independent of the amount of negative sequence injection while the SD-FB operational cost will increase linearly as the negative sequence reactive power is increased.

Figure 6: Total capital expenditure comparison of the discussed configurations.

The average price per kilowatt-hour is taken according to official statistics for 2015 for the countries inside the Eurozone (~0.12 €/kWh) and is then converted to units. The expected lifetime of the converter system is assumed to be 10 years of operation with the rated power and a duty factor of 10%.

Fig. 7 adds the operational cost (OPEX) of the two configurations to the previously extracted capital expenditure (CAPEX). In this graph the STATCOM is assumed to be providing only positive sequence reactive power which is the best case scenario for the SD-FB configuration.

Figure 7: Total cost comparison of the discussed configurations for 10 years operation with rated power.

It is clear in Fig.7 that the higher losses in the SD-FB configuration increase the operational cost that finally even with the best case scenario of injecting only positive sequence current, the total cost of this configuration is slightly higher in comparison to the DS-HB converter. A more realistic scenario of injection would result in further increase in the operational cost of the DS-FB converter, as discussed previously.

Finally, Fig. 8 shows the total cost in units as a function of the time in years for both configurations. It can be seen that in the best case scenario when only positive sequence injection is considered, the DS-HB becomes more profitable after approximately 7.5 years of operation.

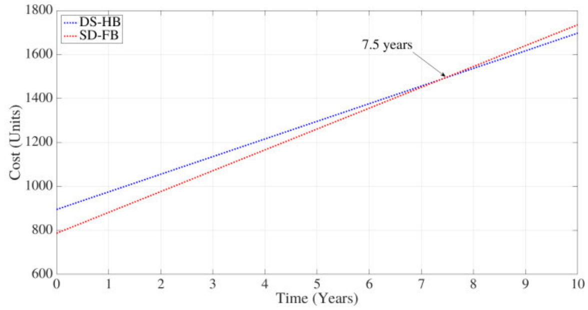

Figure 8: Total cost comparison per year.

VI. Discussion

In this paper, an in depth comparison of the DS-HB and SD-FB configuration in their application as large utility grade STATCOMs, able to control *1 pu* negative sequence reactive power, was made. It should be highlighted that the current analysis used a low-cost 1.7kV commercial IGBT. These devices are known for their low price/MVA ratio, their low switching times that allow higher maximum modulation indexes and lower switching losses in comparison to their MV counterparts. On the other hand, this choice leads to the need for large capacitors that as shown in the cost analysis section, dominate the capital expenditure of the discussed topologies

A final evaluation of the two topologies in terms of losses and cost is shown in radar diagram form in Fig. 9 that follows. In this Figure, PSI stands for positive sequence injection and NSI for negative sequence injection.

Figure 9: Performance evaluation of the discussed configurations

Based on the conducted analysis it can be concluded that the DS-HB is the preferred topology for a STATCOM application when the full negative sequence current needs to be exchanged with the grid. Finally, it should be highlighted that many components that are associated with the CAPEX were left outside of the cost analysis and may significantly increase the initial cost. The exact estimation of the total cost however was outside of the scope of this paper that aimed to compare the discussed topologies.

References

[1] K. Fujii, U. Schwarzer, R.W. de Doncker, "Comparison of Hard-Switched Multi-Level Inverter Topologies for STATCOM by Loss-Implemented Simulation and Cost Estimation," *in Power Electronics Specialists Conference*, pp.340–346, 2005.

[2] M. Hagiwara, R. Maeda and H. Akagi "Theoretical Analysis and Control of the Modular Multilevel Cascade Converter Based on

Double-Star Chopper-Cells (MMCC-DSCC) ", *Conf. Rec. IPEC-Sapporo*, 2010.

[3] Betz R, Summers T.: "Introduction to Symmetrical Components and their use in STATCOM Applications", ResTech Pty Ltd School of Electrical Engineering and Computer Science University of Newcastle, Australia 2009.

[4] M. Hagiwara, R. Maeda and H. Akagi "Negative-Sequence Reactive-Power Control by a PWM STATCOM Based on a Modular Multilevel Cascade Converter (MMCC-SDBC)", *Energy Conversion Congress and Exposition (ECCE)*, *IEEE*, pp. 3728-3735, 2011.

[5] E. Behrouzian, M. Bongiorno and H. Z. De La Parra, "Investigation of negative sequence injection capability in H-bridge multilevel STATCOM," *Power Electronics and Applications (EPE'14-ECCE Europe), 2014 16th European Conference on*, Lappeenranta, 2014, pp. 1-10.

[6] Infineon IGBT, *FF600R17ME4*.

[7] N. Ahmed, L. Angquist, A. Antonopoulos, L. Harnefors, S. Norrga, H.S. Nee, "Performance of the modular multilevel converter with redundant submodules", in *Industrial Electronics Society*, 2015

[8] K. Ilves, S. Norrga, L. Harnefors, and H.-P. Nee, "On energy storage requirements in modular multilevel converters", *IEEE Trans. Power Electron., vol. 29, no. 1*, pp. 77–88, Jan. 2014.

[9] J. Kolb, F. Kammerer, and M. Braun, "Dimensioning and design of a modular multilevel converter for drive applications", in *Proc. 15th Int. Power Electron. Motion Control Conf.*, pp. 1–8, 2012.

[10] Q. Tu, Z. Xu, H. Huang, and J. Zhang, "Parameter design principle of the arm inductor in modular multilevel converter based HVDC", in Proc. *International Conference on Power System Technology*, pp. 1–6, 2010.

[11] Kemet, ALS 30/31 Series, *ALS30A682NT500.*