Device Loading of a Modular Multilevel Converter in Wind Power

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Modular multilevel converter (MMC) is a recently emerged multilevel topology for high-voltage high-power applications. However, in wind power applications, to the best of the authors knowledge, the performance of the MMC has not been extensively investigated. In this paper, the application of the MMC to wind energy systems is studied. The converters used to connect the wind turbine to the grid, which have rated active powers of 2 MW and 10 MW, are proposed and investigated. The electrical losses and thermal loading of the power devices in the proposed converter solutions are analyzed based on the grid conditions/requirements for wind power. The efficiency of the MMC under different $P/Q$ boundaries defined by grid codes is investigated and compared with two-level (2L) and three-level (3L) neutral point clamped converters. It is concluded that it is possible to use the MMC in wind power applications, and the losses are evenly distributed between the submodules of the MMC. However, inside a submodule, the losses of the power devices are not equal, which may lead to the de-rating of the converter.

Keywords: MMC converters, renewable energy sources, thermal stresses, wind power generation

1. Introduction

The number of wind turbines installed worldwide has been growing constantly over the last few decades. As the power capacity of wind turbines has increased up to 10 MW, the connection to the grid by traditional 2L converters requires a large number of series- or parallel-connected power devices in order to achieve the required power. This decreases the reliability of such a converter while the complexity increases. Multilevel converters are known to be a promising solution in wind turbine applications because of their ability to work with higher output voltage levels and thus obtain larger output powers using the power devices available at present.

Among various multilevel topologies such as the Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB), the Modular Multilevel Converter (MMC) is a fairly new topology, introduced in 2002. The advantages of the MMC that make it an attractive solution for wind power generation systems are their modular design, redundancy, simple voltage scaling, and possibility to connect the converter directly to the grid without a transformer. While the application of the MMC converter to high-voltage DC (HVDC) transmission systems is well reported in the literature, not many papers have been published about the application of this topology to wind turbines.

A thorough analysis of the MMC converter is required in order to investigate the suitability of the topology for wind power systems.

In this paper, two different MMC concepts are proposed to investigate the performances and opportunities of this topology being applied to a wind power application. The first one is based on typical low-voltage (690 V) 2 MW wind turbines with minimum component counts and volumes, with the aim to investigate the opportunity to replace the traditional 2L and 3L topologies by such an MMC configuration. The second one is a 10 kV 10 MW solution targeted at the next generation of wind turbines that are closer to the HVDC application. In this solution, the maximum/future potentials of this MMC configuration for wind power are analyzed. In this paper, the two different concepts are designed based on wind power specifications and are compared with 2L/3L topologies with respect to grid codes.

In the wind power application there are two converters configured in a back-to-back structure (Fig. 1 and Fig. 2). This study concentrates on the grid-side converter, where the grid code impacts, voltage/current ratings, and converter designs are special considerations based on the wind power application. As the powers are increasing, the reliability and power density aspects of the converter are of great importance for high-power wind turbines, which are typically installed off-shore in remote and harsh environments. These aspects are affected by the loading and thermal performance of the switching power devices, which are studied in this paper.

2. Modular Multilevel Converter for a Case Study in a Wind Application

A simplified schematic of the MMC used in a wind power application is presented in Fig. 1. The topology is based on the series connection of submodules (SM). The number of SMs is the same in each phase arm.
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Fig. 1. Simplified schematic of the MMC for a wind turbine application

The circuit diagram of a half-bridge SM, which contains a floating DC capacitor and two IGBTs with free-wheeling diodes is also presented in Fig. 1. The basic operation principles of the MMC converter are well documented in the literature.

2.1 Selection of the Components

Considering the operating principles of the MMC converter, the IGBT modules and the capacitors of the SMs have to be selected according to the rated voltage

\[ U_{SM} = \frac{U_{DC}}{N} \]

where \( U_{DC} \) is the DC link voltage and \( N \) is the number of SMs in an arm. A safety margin has to be taken into account to ensure in order to have some redundancy.

The selection of the SM capacitor is a compromise between the capacitor size, cost, and the voltage requirements. The capacitance of the SM capacitor can be calculated based on the desired voltage ripple factor \( \varepsilon \) having a value between 0 and 1

\[ C_{SM} = \frac{\Delta W_{SM}}{2 \cdot \varepsilon \cdot U_{SM}^2} \]

where \( \Delta W_{SM} \) is the energy change in one SM, which is estimated by

\[ \Delta W_{SM} = \frac{2}{3} \cdot \frac{S}{k \cdot \omega_n \cdot N} \left( 1 - \frac{k \cdot \cos \varphi}{2} \right)^{3/2} \]

where \( S \) is the apparent power of the converter, \( \omega_n \) is the output angular frequency, \( k \) is the voltage modulation index, \( N \) is the number of SMs in an arm, and \( \cos \varphi \) is the power factor (PF).

The arm inductors \( L_{arm} \) are used in the MMC converter to suppress the circulating currents and to limit the fault current during a short circuit between the DC link terminals. The analytical expressions for the calculation of the arm inductance based on these two issues are given in a study by Tu et al. \(^{(a)}\). In this paper, the value of the arm inductance is selected to be 0.15 per unit, which is a commonly used value for the MMC converter \(^{(a)}\). However, it should be controlled that the selected SM capacitance and the arm inductance do not produce a resonance \(^{(a)}\).

2.2 Low-voltage Solution for a Wind Power Application

A converter with a minimum number of SMs in a phase leg is not presented in the literature; however, this solution may be beneficial owing to the lower component counts in comparison with the MMC having more SMs. Thus, the first grid-side converter under study has a rated power \( P \) of 2 MW and only two SMs in a phase leg. This converter produces 690 V line-to-line voltage and is used to connect a low-voltage generator to the grid (Fig. 2). It can be an alternative to the existing 2L wind power converter based on 690 V grid voltage. The parameters of the converter and the ratings of the selected IGBT module 5SNA 1800E170100 by ABB \(^{(11)}\) are summarized in Table 1.

The converter is simulated by Matlab/Simulink and PLECS Blockset \(^{(12)}\). Level-shifted pulse-width modulation (PWM) is applied to obtain the desired arm voltage. For simplicity, the reference to the modulator is generated using a direct strategy \(^{(13)}\). Simulated waveforms are shown in Fig. 3. The power factor of the grid-side converter is selected to be \( PF = 1 \) (Fig. 3).

2.3 High-voltage Solution for a Wind Power Application

The second solution of the MMC converter is a converter with ten SMs in a phase leg. As the power capacity grows quickly, this converter is suitable for a high-voltage application, which is a preferred choice for the next-generation wind turbines with 10 MW rated power. This converter generates 10 kV line-to-line voltage using an IGBT module 5SNA 0600G650100 by ABB \(^{(11)}\). An equal voltage sharing among the capacitors in each arm is ensured by applying a selection mechanism \(^{(14)}\). The selection of the SM to be inserted or bypassed is made based on the measured
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Fig. 3. Output current, phase voltage, and line-to-line voltage of the 2 MW MMC converter ($P = 2$ MW, $PF = 1$)

Table 2. Parameters of the simulated 10 MW MMC grid-side converter

| Parameter                           | Value          |
|-------------------------------------|----------------|
| Number of SMs per arm               | 5              |
| Rated line-to-line voltage, kV      | 10             |
| DC voltage, kV                      | 16.3           |
| Rated current, A                    | 577            |
| Arm inductance, mH                  | 4.8 (0.15 p.u.)|
| SM capacitance, mF                  | 3.2            |
| Carrier frequency, Hz               | 1050           |
| Filter inductance, mH               | 0.95 (0.03 p.u.)|
| IGBT module                         | ABB 55N 0600G650100 |
| IGBT commutated voltage, kV         | 3.6            |
| IGBT maximum current, kA            | 9.6            |
| Number of IGBT modules              | 60             |
| Total MVA rating of all IGBT modules| 130            |

Fig. 4. Output current, phase voltage, and line-to-line voltage of the 10 MW MMC converter ($P = 10$ MW, $PF = 1$)

3. Loading of Power Devices

The current, loss, and thermal distributions of the converters under study are considered in order to analyze the loading of the devices.

3.1 Current Distribution

Current distributions among the power devices in one SM of the 2 MW and the 10 MW converters operating with $PF = 1$ are presented in Fig. 5 and Fig. 7.

It is shown in Figs. 5 and 7 that the current of the switching devices is about half of the peak output current of the converter. Thus, even though the MMC converter with two SMs has two voltage levels similarly as a traditional 2L converter, the switching devices with a lower rated current can be chosen for the MMC converter with the same rated power as a two-level converter.

Uneven current distribution between the power devices of the SM is observed. As shown in Fig. 5, the upper diode $D_U$ and the lower IGBT $T_L$ are heavily loaded when the converter operates with $PF = 1$. When the converter operates with $PF = -1$ (Fig. 6), the upper IGBT $T_U$ and the lower diode $D_L$ are mostly loaded. Uneven current distribution among the power devices in the SM is explained by the presence of a DC component $i_{dc}$ in the upper and lower arm currents $i_u$ and $i_l$, which equals one-third of the total DC current and provides the actual DC to AC power transfer (or AC to DC when
Apart from the DC and AC components $i_{dc}$ and $i_{ac}$, the arm currents $i_u$ and $i_l$ (Fig. 1) also contain a double-line frequency component, which is called the circulating current $i_{circ}$ as presented in Moon et al. \(^{(15)}\):

\[
i_u = i_{dc} + \frac{i_{ac}}{2} + i_{circ} \tag{4}
\]

\[
i_l = i_{dc} - \frac{i_{ac}}{2} + i_{circ} \tag{5}
\]

\[
i_{ac} = i_u - i_l \tag{6}
\]

The circulating current does not influence the output current but increases the rms value of the arm currents, and consequently, also increases the losses. The suppression of the circulating current has been under research over the last decade, and several control methods have been proposed\(^{(13)}(16)(17)\). In Fig. 8, the current distribution among the devices of the SM of the 2 MW MMC converter with the distributed control proposed by Hagiwara and Akagi\(^{(16)}\) is shown. The double-line frequency component in the arm current is suppressed, but the unequal loading has become even more severe.

### 3.2 Loss Distribution

The loss model presented by Ma et al. \(^{(18)}\) is applied, and the simulation is carried out in PLECS Blockset in Simulink\(^{(12)}\). The loss distribution of the SM of the 2 MW converter without a circulating current control is shown in Fig. 9. It is observed that the losses among the devices in the SM are unequally distributed. As shown in Fig. 10, the losses of the converter SM with the circulating current control are lower, but the unequal loading is more significant. Figure 11 illustrates the loss distribution of the SMs of the 10 MW converter. While the losses in the SM are still unequally distributed, the loss distribution between five SMs of the arm is quite uniform. It is noted that equal loss distribution among different SMs is achieved by applying a selection mechanism for the voltage sharing between the SM capacitors, as shown in Fig. 11.

### 3.3 Thermal Distribution

Thermal performance of the power devices is of great importance in high-power wind turbine converters since it directly affects the converter reliability, power density, and the cost of the system. Accurate estimation of the temperatures of the power devices is possible only with an appropriate a good thermal model. In this paper, the thermal model (Fig. 12), which is able to estimate both the case and junction temperatures is employed\(^{(18)}\). The thermal parameters of the multilayer Foster model of the power device impedances are taken from the datasheets and summarized in Tables 3 and 4\(^{(11)}\). A liquid cooling system...
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Fig. 11. Loss distribution in the SMs of the upper arm of the 10 MW MMC converter (TU – upper IGBT, DU – upper diode, TL – lower IGBT, DL – lower diode)

Table 3. Thermal impedance of the IGBT module 5SNA 1800E1700

| Thermal impedance | $Z_{(0)}$ | Layer 1 | Layer 2 | Layer 3 | Layer 4 |
|-------------------|----------|---------|---------|---------|---------|
| $R_{on}, \; \text{kW}$ | 6.24     | 1.73    | 0.704   | 0.345   | 6       |
| $V_{on}, \; \text{mV}$ | 192      | 204     | 1.97    | 0.52    |         |
| $R_{on}, \; \text{kW}$ | 11.6     | 2.91    | 1.28    | 1.27    |         |
| $V_{on}, \; \text{mV}$ | 204      | 29.3    | 6.96    | 1.5     |         |

Table 4. Thermal impedance of the IGBT module 5SNA 0600G650100

| Thermal impedance | $Z_{(0)}$ | Layer 1 | Layer 2 |
|-------------------|----------|---------|---------|
| $R_{on}, \; \text{kW}$ | 8.5      | 2       | 6       |
| $V_{on}, \; \text{mV}$ | 151      | 5.84    |         |
| $R_{on}, \; \text{kW}$ | 17       | 4.2     |         |
| $V_{on}, \; \text{mV}$ | 144      | 5.83    |         |

Fig. 12. Thermal model of the power device module

is used to dissipate the thermal losses, and the fluid temperature is assumed to be 40°C. The estimated temperatures of the power devices of the SM of the 2 MW and 10 MW converters are presented in Figs. 13 and 14. It is evident that the temperatures of the devices are related to the losses presented in Fig. 9 and Fig. 11. The observed unequal temperatures of the power devices in the SM may lead to the derating of the power converter and a decrease in the converter power capability. They are also the major weakness of the whole converter with respect to reliability.

4. Converter Efficiency under Different $P/Q$ Boundaries

As a result of the high penetration of wind turbine systems in many countries, strict regulations on the performance of wind power converters under normal and fault operation have been introduced. Thus, the reactive power delivered by a wind turbine has to be regulated within a certain range. The widest ranges are found in a German grid code, where three variants of the allowed boundaries of reactive power versus active power are defined as presented in Fig. 15(19).

Usually, the variant is chosen in agreement with the grid operator. As it can be seen in Variant 1, the underexcited reactive power should be less than 23% of the rated active power $P_{\text{rated}}$, and the overexcited reactive power should be less than 48% of $P_{\text{rated}}$.

In order to analyze the suitability of the MMC converter for a wind application, the efficiency of the converter under different active powers is studied. The MMC converter with two SMs in a phase leg (Table 1) is compared with 2L and 3L NPC converters having the parameters presented in Table 5. The efficiencies of three converters are presented in Fig. 16, which illustrates the cases when the converters operate within underexcited and overexcited reactive power boundaries of Variant 1 and without reactive power. It is observed that the efficiency of the converters at a low active power is lower when the grid code requirements for extra reactive power are
met. The 3L-NPC converter shows a slightly better efficiency than the 2L and MMC converter. However, the implementation of the main circuit of the 3L-NPC converter is more challenging regarding the stray inductance minimization of the converter commutation loops. While the commutation loops of the MMC and 2L converters have two IGBT modules and a capacitor, the commutation loops of the 3L-NPC contain up to four IGBT modules and a capacitor. Thus, the higher number of components makes the stray inductance minimization more difficult to implement (10). In turn, the volume of the MMC converter is larger because of the large capacitors. It is pointed out that by varying the switching frequency of the power devices, the efficiency of the converters can be adjusted, and the filter size has also to be taken into account.

5. Conclusions

In this paper, two solutions of wind turbine converters based on the MMC topology were evaluated. The first solution has a minimum number of SMs and requires only 12 IGBT modules (3x2x2N). This solution may be more feasible for a wind application where the converter is installed in the nacelle and the size is a critical factor, although in an HVDC application where the space is not an issue, the MMC with a large number of SMs is a popular choice. The second solution has ten SMs in a phase leg with 60 IGBT modules.

The analysis of the converters was based on a study of the loading and thermal performances of the switching devices. The efficiency of the MMC converter under different $P/Q$ boundaries defined by grid codes was presented.

It was observed that the losses were uniformly distributed between the SMs of the MMC converter with ten SMs. However, severely unequal loss distribution between the devices in a SM was detected, which may lead to a derated converter power capacity in an actual design case.

The requirement of extra reactive power modifies the loss distribution of the power devices, and a lower efficiency of the converter at a low active power was observed.

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**Fig. 15. $P, Q$ range of a wind power converter defined by a German grid code**

**Fig. 16. Efficiency of the 2L, 3L-NPC, and MMC converters under different $P/Q$ boundaries defined by a German grid code (Variant 1)**

**Table 5. Parameters of the simulated 2L and 3L-NPC grid-side converters**

|                     | 2L       | 3L-NPC  |
|---------------------|----------|---------|
| Rated active power, MW | 2        | 2       |
| Rated line-to-line voltage, kV | 0.69     | 0.69    |
| DC voltage, kV       | 1.1      | 1.1     |
| Rated current, A     | 1674     | 1674    |
| Carrier frequency, Hz | 3450     | 1050    |
| Filter inductance, mH | 0.15 (0.2 p.u.) | 0.15 (0.2 p.u.) |
| IGBT module          | ABB SSNA | Infineon |
|                      | 2400E170100 | FZ2400 |
|                      | R125E49B  |         |
| IGBT commutated voltage, kV | 1.1      | 0.6     |
| IGBT maximum current, kA | 2.4      | 2.4     |
| Number of IGBT modules | 6        | $12 + 6^1$ |
| Total MVA rating of all IGBT modules | 16      | 26      |

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