Design of High-Reliable Converters for Medium-Voltage Rolling Mills Systems

Victor de Nazareth Ferreira*, Allan Fagner Cupertino* †, Heverton Augusto Pereira‡, Anderson Vagner Rocha†, Seleme Isaac Seleme Junior* and Braz de Jesus Cardoso Filho*

*Graduate Program in Electrical Engineering - Federal University of Minas Gerais
Av. Antônio Carlos 6627, 31270-901, Belo Horizonte, MG, Brazil
Emails: vnferreira89@gmail.com, seleme@cpdee.ufmg.br, braz.cardoso@ieee.org
†Federal Center for Technological Education of Minas Gerais
Av. Amazonas 5253, 30421-169, Belo Horizonte, MG, Brazil
Emails: afcupertino@ieee.org, andersonrocha@des.cefetmg.br
‡Department of Electrical Engineering - Federal University of Viçosa
Av. P.H. Rolfs, 36570-901, Viçosa, MG, Brazil
Emails: heverton.pereira@ufv.br

***Abstract*—Steel is nowadays the world's most important industrial material, with over 1.5 billion tonnes produced annually. In metal industry, rolling is the most widely used steel forming process to provide high production and control of final product. In large drive systems for rolling mills, important requirements such as fast dynamic response and high overload capacity are achieved by using high power converters in medium-voltage range. Among the existing high power multilevel converters, the Neutral Point Clamped (NPC) is the most accepted in industry and the Modular Multilevel Converter (MMC) has been highlighted in recent years for its highest voltage capability, power ratings, high modularity and scalability. This work suggests a methodology of selection and design of high-reliable power converters for critical applications. Two converters are compared with the standard solution: the fault tolerant version of the active NPC converter (FT-ANPC) and the Triple-Star Bridge Cells Modular Multilevel Converter (TSBC-MMC). The study is performed with data taken from a big steel industry in southeastern Brazil. It is demonstrate that FT-ANPC has lower cost. However, TSBC-MMC presents lower power losses and can survive to more failures.**

I. Introduction

Rolling mills must be able to vary the speed of the strip at the same time that the speed is controlled within precise limits. This characteristic could be easily accomplished with dc motors. However, the introduction of alternating current (ac) for power transmission and distribution levels meant that some means had to be provided to produce dc power [1]. In 1921, Scherbius drives were applied in a significant fraction of rolling mills [2]. The double-range Scherbius control had the ability to slightly adjust the speed of machines with a minor variation of frequency on either or both systems. Solid-state power conversion equipment for high power became available in the 1960s. Dc rolling mill motors were built in the range of 16,000 HP. However, recently the pendulum has swung back toward ac drives as new techniques for precise speed control of these machines have been developed [1]. Ac electric drive control techniques, considering the load impact of rolling mills, are proposed in [3] and [4].

Nowadays, ac medium-voltage (MV) power converters play a vital role to meet many demands of the modern industry. In the MW range, medium-voltage drives are preferred due to their higher efficiency and higher power density [5]–[7]. The importance of these equipment in critical industrial processes culminated in extraordinarily high availability requirements. For about 30 years, the three-level neutral-point-clamped voltage-source (3L NPC VSC) converter has been the standard solution in the medium-voltage range for industrial applications [8]. Generally, double stator synchronous machines are employed to drive the mill. Since the drive is reversible, back-to-back connection of NPC converters are employed in many mill systems in the southeastern Brazil. The diagram of this system is presented in Figure 1.

Nevertheless, the NPC converter has an inherent problem in the distribution of losses between phase switches, which can reduce its power capacity, and compromise the semiconductors reliability. Furthermore, this topology does not have redundancy, which means that the system operation is interrupted under a failure situation. Working almost 365 days annually, steel industry requires high-reliable systems since out-of-service maintenance incurs extra costs. In addition to the high cost/failure rate, rolling mills have a critical dynamic loading, making the design of reliable converters doubly challenging.

Hence, this work intends to establish a methodology for design and selection of high-reliable converters for applications with critical mission profile, as shown in Figure 2. The first step is to characterize the application, collecting the system parameters as well as its mission profile. With this data, the converter topology is selected. The design for reliability (DFR) is implemented for the critical components. Cost and losses analysis are the final selection criteria. Each procedure is detailed step-by-step to allow industrial engineers

978-1-5090-4894-6/17/$31.00 © 2017 IEEE

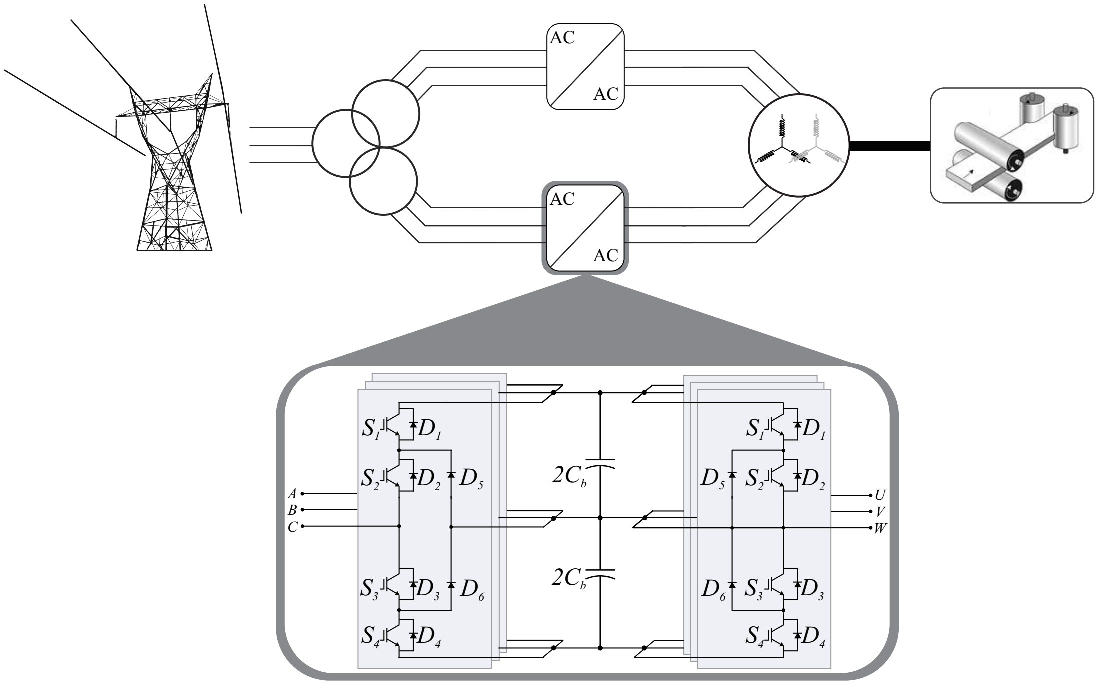

Fig. 1. Schematic for the mill system located in the southeastern Brazil with the standard solution.

to perfectly understand and implement this methodology.

The outline of this paper is as follows. Section II discuss the characteristics of the mission profile employed in the case study. Section III presents the important features of the FT-ANPC and the TSBC-MMC topologies. Section IV presents the application of the design methodology proposed and the thermal stresses in the studied topologies. Finally, Section V presents the losses and cost analysis. The conclusions are stated in Section VI.

II. Mission Profile and System Parameters

The schematic of the rolling mill diagram is shown in Figure 1. In order to exemplify the proposed methodology, it is adopted a case study of a 7 MW rolling mill system installed in the southeastern Brazil. This system is based on a dual stator winding synchronous machine, whose parameters are reported in Table I. The overload capability can reach 250 % for 20 seconds.

TABLE I
Parameters of the dual winding synchronous machine employed in the rolling mill system.

Operating Data	Rated Point	Max. Cont.	Peak (20 s)
Output (MW)	7	8	17.5
Line Voltage (V)	3150	3150	3150
Frequency (Hz)	8.5	8.5	25.5
Line Current (A)	$667A$	774	1815
Power Factor	0.99	0.99	1
Speed (min^{-1})	85	85	255

The mission profile of the rolling mill system is analyzed over a full day operation, 8 hours of functionality with three stops and the lamination of about 60 steel parts. The mechanical speed n_m and the rms value stator current I_s were obtained from measurements of a 7 MW rolling mill system. The data are sampled each 100 ms. The per-unit (pu) values [1] are presented in Figure 3. As clearly observed, this application has a really critical load cycling, with a strong current variation.

In the power losses modeling, the output voltage synthesized by the converter are necessary. The converter voltage is estimated through the mechanical speed. Basically the machine frequency is obtained using the pole number. After, a control strategy based on scalar control (V/Hz) with field weakening operation is assumed. Therefore, the voltage is proportional to the frequency until the rated point. After, the voltage e maintained constant and the frequency is increased.

III. Power Converter Selection

In this section are presented two high-reliable topologies that can be chosen for MV rolling mill system. The first one is the FT-ANPC converter, that has been shown to be very promising for high-power mission critical applications [9] [10]. The second one is the Triple-Star Bridge Cells Modular Multilevel Converter (TSBC-MMC), which is emerging as a promising high-reliable solution for electrical drives with high torque requirements at low speeds [11], [12]. The topologies features are detailed, highlighting their fault tolerance capability and control strategies.

[1]Bases: $255min^{-1}$ for mechanical speed and 1815 A for stator current.

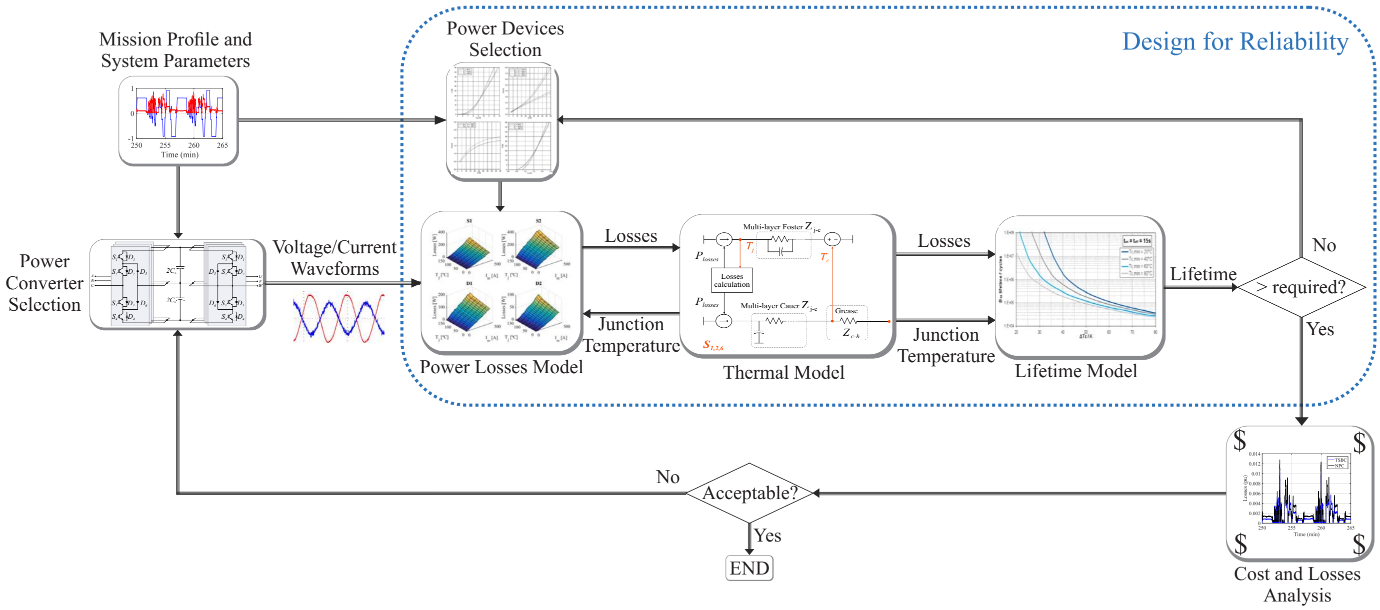

Fig. 2. Methodology for design and selection of high-reliable converters for mission critical applications.

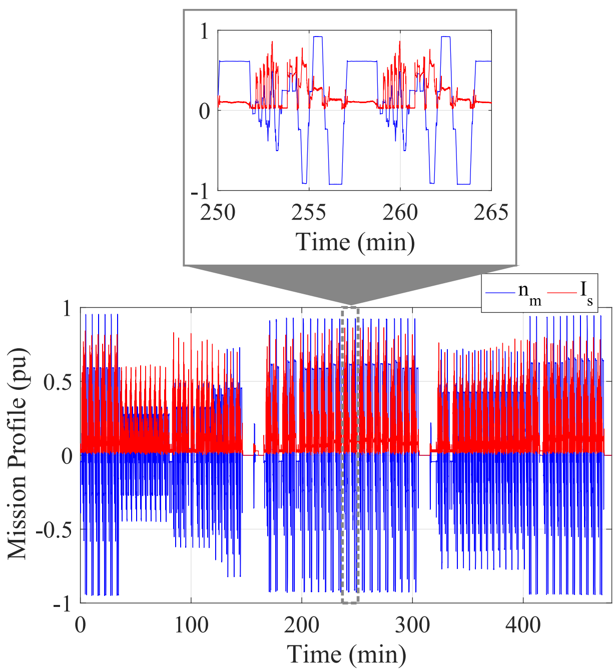

Fig. 3. Mission profile of a lamination process.

A. Fault-tolerant ANPC

In 2001, the 3L Active Neutral Point Clamped (ANPC) converter was introduced to overcome the main structural drawback of the 3L-NPC VSC, regarding the power losses distribution [13]. The proposed topology employs two extra active switches per phase compared to the original NPC structure, as shown in Figure 4. The additional active switches add new commutation modes, allowing substantial improvement of the loss distribution among the converter power devices [14], [15]. As a result, the output power can be increased by up to 25%, by using 3L-ANPC VSC [15]. The FT-ANPC concept is based on the premise that the ANPC structure can be designed aiming to overcome failure situations and to extend the converter lifetime. These benefits are achieved by adding minimal additional parts and using existing connections in the commercial well known ANPC converter [10]. As can be seen in Figure 4, two IGBTs (S_5 and S_8) with their respective free-wheeling diodes (D_5 and D_8) are added per phase. Also, a switch (K_c) with two reversible contacts is introduced. The K_c is not a critical device since it is comutated under zero current, and can be implemented with simple contactors or manual operated switches. With these extra components, the new topology of neutral point clamped converter is capable of changing its configuration in multiple ways.

Phase legs L_1 and L_2 can operate in two different complementary modes through K_c: Phase (P) and Neutral (N). For example, if L_1 is connected to the neutral point (N), L_2 is necessarily connected to the phase point (P), and vice-versa. Since this converter operates as a NPC or ANPC, some simple reconfigurations can also be made. The external devices of the right leg (S1 and S4) can be interchanged with the external devices of the right leg (S_5 and S_8) by software. To interchange the internal devices (S_2/S_3 and S_6/S_7), it is necessary to stop the converter switching allowing the current to go to zero. Thus, K_c can be switched, changing the connection of L_1 and L_2. From its reconfiguration capabilities, the FT-ANPC converter has been shown to be able to prolong considerably the power devices lifetime, and to survive up to four consecutive failure situations in one phase, without compromising the load operation, before to shutdown the converter. Figure 4 shows a back-to-back structure composed by two FT-ANPC converters.

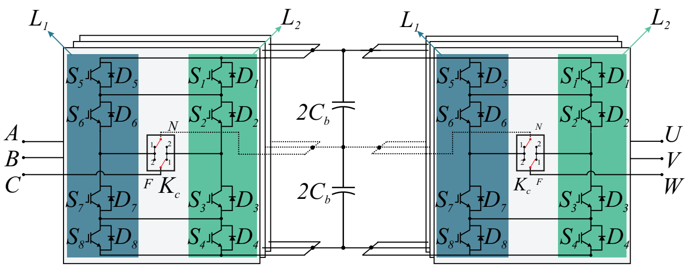

Fig. 4. Schematic of back-to-back fault-tolerant ANPC converter.

1) Control Strategy: Since the FT-ANPC converter does not present circulating current, simpler control strategies can be adopted. The three-level space vector pulse width modulation (SVPWM) [16] and the ANPC feedforward loss control [17] are used to obtain the required output voltage and improve the losses distribution. The variable frequency control of the induction machine can be achieved by using the common vector control technique [18]. The three-phase ac/dc stage control is based on a cascade strategy, as described in [19]. The internal control loops regulates the grid currents while the outer control loop regulates the dc-link voltage and the reactive power injected in the main grid. During the braking process, the rectifier is responsible to inject the energy into the grid.

B. TSBC-MMC

The modular multilevel converters (MMC) family is considered as one of emerging high power converters for medium voltage drives. The MMC concept is to obtain a high voltage converter using a cascade connection of low voltage units, called cells or submodules (SMs). The first MMC topology discussed in literature for medium voltage drives is based on the double-star chopper cells modular multilevel converter (DSCC-MMC). However, this topology presents some limitations in low speed region. Basically, when the converter synthesizes low frequencies, the voltage ripples across the SM capacitors increase considerably. Additionally, higher values of circulating current are necessary to obtain rated torque at standstill. Although some solutions have been proposed to improve the performance of this topology, the DSCC-MMC is not considered a suitable topology for rolling mills applications, where large values of torque are necessary in a very low speed region [20].

For rolling mill applications, the triple-star bridge cells MMC (TSBC-MMC) is more suitable, as discussed in [12], [20], [21]. This topology does not present an increase in voltage ripple or circulating currents in low frequency region. The schematic of TSBC-MMC is presented in Figure 5. As observed, TSBC-MMC presents 9 clusters and enables direct three phase ac-to-ac bidirectional power conversion with any power factors at both sides [11]. This topology is also called as Modular Multilevel Matrix Converter [12].

Each SM contains a capacitance C and eight semiconductor switches (S_1, S_2, S_3, S_4, D_1, D_2, D_3 and D_4). The cluster inductance L is responsible for reducing the high order harmonics in the circulating current and also limiting the currents during faults [22]. The converter presents N SM per cluster. Generally, there is a switch S_T in parallel with each SM, which is responsible for bypassing it in case of failures [23].

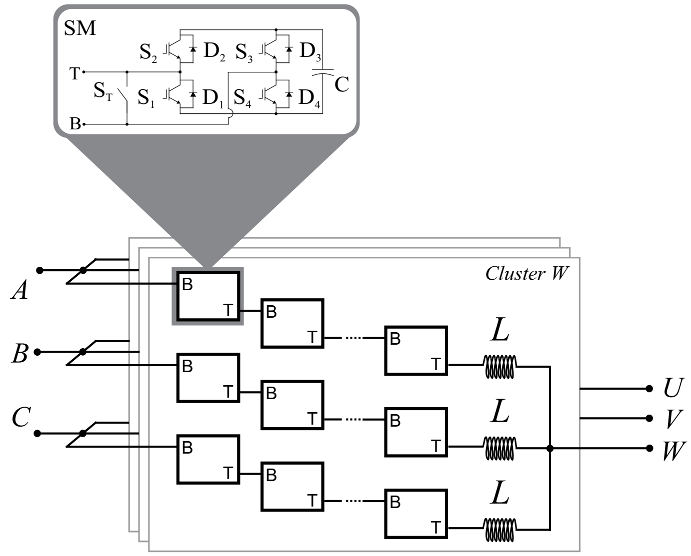

Fig. 5. Schematic of the TSBC-MMC converter.

The TSBC-MMC topology is often featured with its robustness in terms of SM failures. When power switch failures are identified (generally by advanced gate drives), the corresponding SM should be bypassed [24]. In order to ensure that the converter remains operational during failures, some redundancy strategy needs to be included to the converter structure [25]. Therefore, the operation of the converter can continue without affecting the overall performance [26]. This condition is attended for a percent number of SM failures. In most works in literature, the redundancy factor is something around 10 % [27]. It means that the operation of the converter can continue until the failure of 10 % of SMs.

In [28] the MMC redundancy strategies are classified into two schemes: hot reserve and cold reserve. In hot reserve based strategies the redundant SMs operate in the same way as other SMs. When a fault occurs, the faulty SM is bypassed while the MMC keeps working correctly [28], [29]. In cold reserve based strategies the redundant SMs are bypassed and discharged. When a fault occurs, the corresponding faulty SM is bypassed and the redundant SM is inserted into the main circuit [28], [29]. Thereby, the hot reserve based strategies can lead to asymmetrical operation in the converter and larger power losses, while the cold reserve based strategies presents more significant transients during failures.

1) Control Strategy: The control strategy for the TSBC-MMC converter is discussed in details in [12], [21] and can be divided in four main functions: Motor control, mean voltage control, circulating current control and capacitor balancing control [30].

The vector control of the induction motor speed is implemented according to reference [31]. The inner loops are implemented in synchronous (dq) reference frame oriented in rotor flux, resulting in a decoupled control of magnetization flux and torque. The external loops control the motor speed ω^* and the magnetization flux λ_m. This control strategy calculates the output voltage reference.

The mean voltage control structure is similar to the control of NPC ac/dc converter. This loop is responsible for determining the amount of active power which flows to the converter. The reactive power is also controlled, resulting in a full control of the grid current power factor. Inner loops in synchronous reference frame regulates the grid currents

The capacitor balancing control regulates the voltages in all capacitors of the converter. These loops calculates the value of the circulating currents (four circulating currents can be identified), which will result in power exchange between the clusters. By using the circulating currents, it is possible to exchange power between the clusters without affect the input or output currents. Phase-shifted pulse-width modulation is employed. More details about the control strategy can be found in references [12], [21].

IV. Design for Reliability

Design for reliability is the process conducted during the design phase of a component or system that ensures them to be able to perform required level of reliability. It aims to understand and fix the reliability problems up-front in the design process [32]. The industry has been reported that the most fragile components are the power devices, and acclaimed by methods of improvements in its reliability . The motor drive sector works in most cases with a lifetime of 10–20 year, with a reduced proportion having a lifetime of 20–30 years [33]. In this step, the DFR is used to ensure a minimum lifetime of 25 years during the IGBT power modules design. The three proposed solutions are analyzed: NPC, FT-ANPC and TSBC-MMC.

A. IGBT Power Modules Design

The first step to select the IGBT power module is based on the system parameters. For the NPC and FT-ANPC converter, the sizing is to withstand half of the dc-link voltage, while for the TSBC-MMC, it is performed considering a half of the SM nominal voltage. The dc-link voltage is $5.6kV$, while the SM nominal voltage is $890V$. Then, medium voltage power devices ($3300V$) for NPC and FT-ANPC, and low voltage power devices ($1700V$) for TSBC-MMC are selected. In terms of switching frequency, NPC and FT-ANPC converters employs 720 Hz while TSBC-MMC is switched in 525 Hz.

The current capacity of power devices is analyzed through the DFR approach, whose flowchart is exhibited in Figure 2. The selected converter is simulated on Plecs with the rolling mill mission profile shown in Figure 3. The current and voltage are used to extract the losses of the selected power devices, that feed the thermal model. The ambient temperature is considered 40 $^\circ C$. The rainflow algorithm is used to characterize the thermal cycling, provided by the thermal model. Finally, the ABB Hi-Pak IGBT power module lifetime model is used to estimate the $B10$ lifetime, which is the number of cycles where 10% of power modules fail [34]. If the expected lifetime is not achieved, the process is repeated, considering power devices with higher current capacity. When the system is working at the edge of the technology, power modules are inserted in parallel.

For the NPC converter, the required lifetime is ensured with two $5SNA1500E330305$ Hi-Pak power modules ($3300V/1500A$) in parallel. The IGBT junction temperature over a day for the back-to-back converter are shown in Figure 6 for both motor and grid side converters. Only the most stressed devices are show. For motor side converter, the most stressed device is the IGBT S1, which reaches a junction temperature of 79.1 $^\circ C$. For grid side converter, the most stressed device is the IGBT S2, which reaches a junction temperature of 95.3 $^\circ C$.

The FT-ANPC converter is capable of working in ANPC mode, equaling the losses and reducing the highest temperature. Furthermore, their thermal degradation management can prolong the power modules lifetime by about 250% [35]. As can be seen in Figure 7, the temperatures at the most stressed devices is considerably reduced to values smaller than 70 $^\circ C$. Thereby, power modules with a reduced current capacity can be used, reducing the cost without extrapolating the lifetime limits.

The TSBC-MMC converter works at a reduced switching frequency and with low voltage power devices. As a consequence, the power losses is highly reduced, and this converter can ensure the required lifetime without parallelism. As can be seen in figure 8, the junction temperatures at the SMs is relatively low with $1700V/1600A$ power modules.

B. Capacitors Design

Capacitors are the second most critical component in power converters, as reported by industry in [33]. Three types of capacitors are generally available for dc-link applications, which are the Aluminum Electrolytic Capacitors (Al-Caps), Metallized Polypropylene Film Capacitors (MPPF-Caps) and high capacitance Multi-Layer Ceramic Capacitors (MLC-Caps). The dc link design requires the matching of available capacitor characteristics and parameters to the specific application needs under various environmental, electrical and mechanical stresses [36]. The dc link of the NPC and FT-ANPC converters installed in the rolling mill is composed by 12 Al-Caps of $2800V$ and 2 mF, totaling 6 mF of equivalent capacitance. The reliability-oriented design procedure for capacitors in dc links [36], is strongly recommended to be used during the DFR process of high-reliable converters.

The TSBC-MMC does not have a dc-link due to its direct ac-ac conversion. Nevertheless, the sub-module capacitor bank design is a critical point for this topology, since there is a high

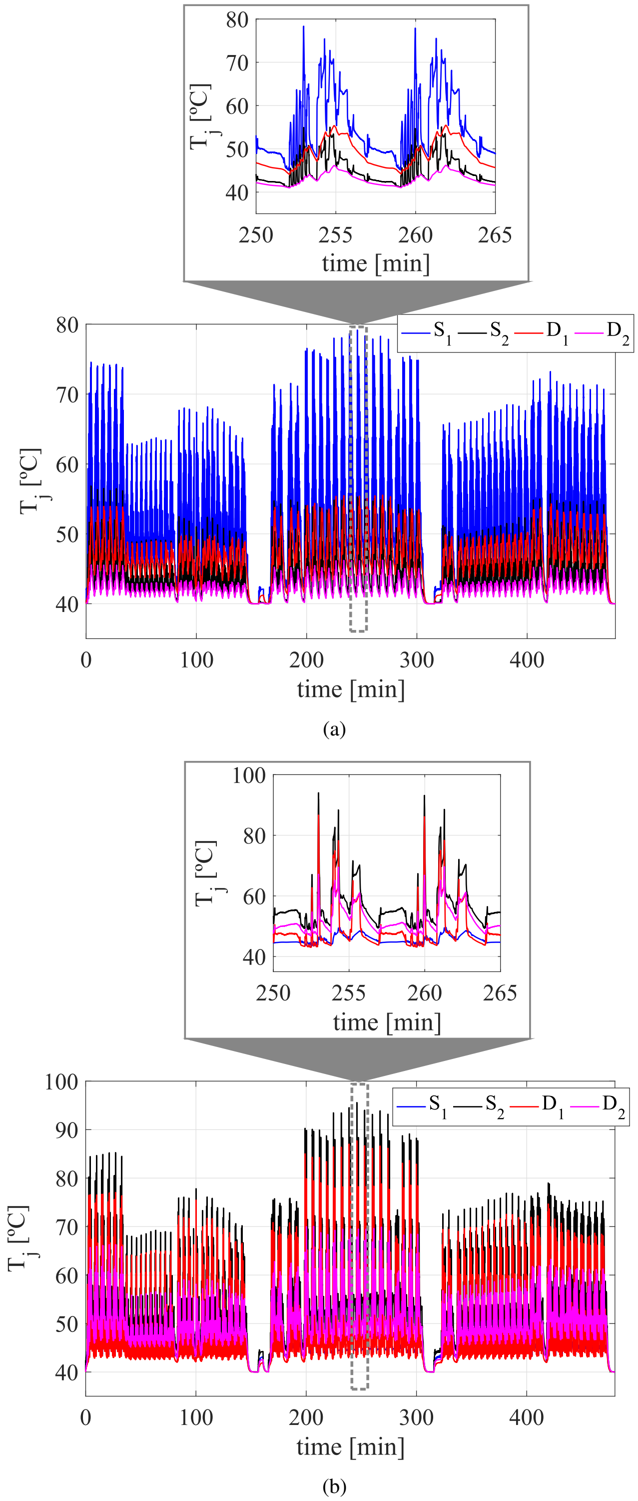

Fig. 6. Power devices junction temperatures of back-to-back NPC converter: (a) Motor side converter; (b) Grid side converter.

ac circulating current passes through it. This high circulating current causes over stress on the capacitor and easily can make failure for each module [37]. The modular multilevel converter considered in this work presents 6 SMs per cluster. Therefore,

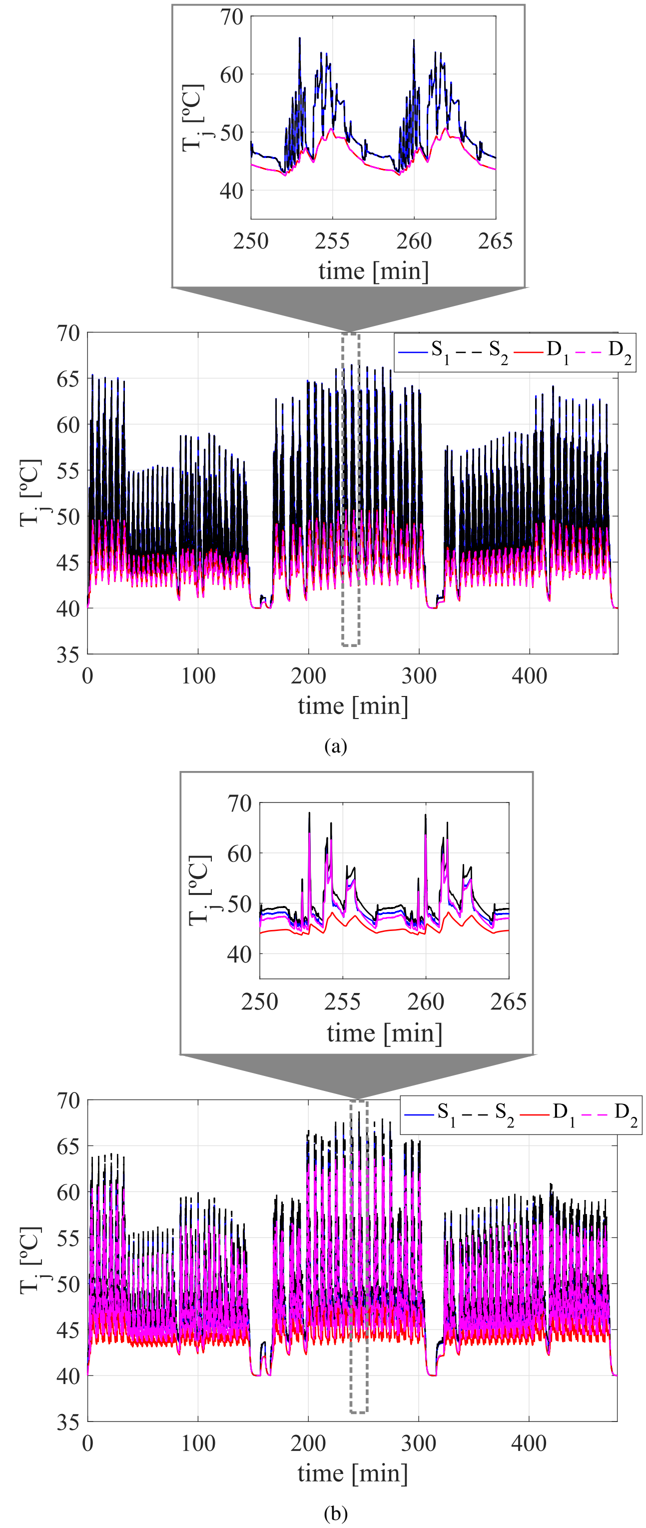

Fig. 7. Power devices junction temperatures of back-to-back FT-ANPC converter: (a) Motor side converter; (b) Grid side converter..

the nominal voltage in each SM is $890kV$. Regarding the SM capacitances for MMC, reference [38] suggests that the maximum energy storage requirement is 40 kJ/MVA, which

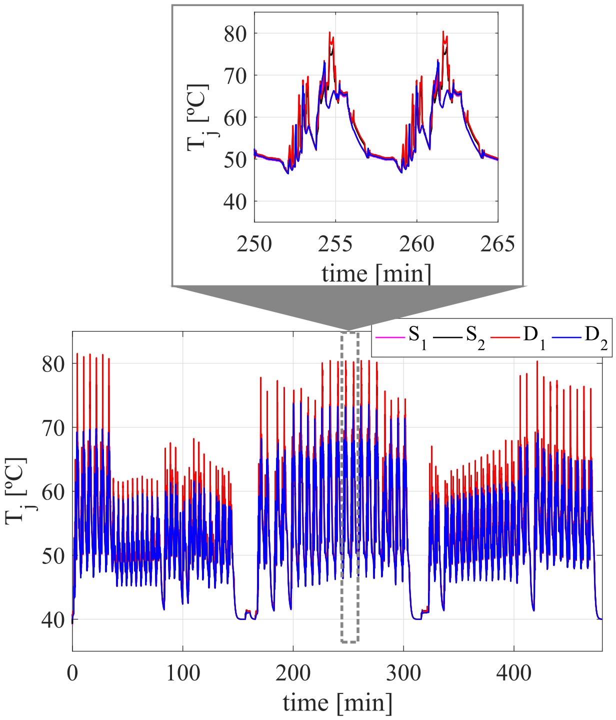

Fig. 8. Power devices junction temperatures of the TSBC-MMC.

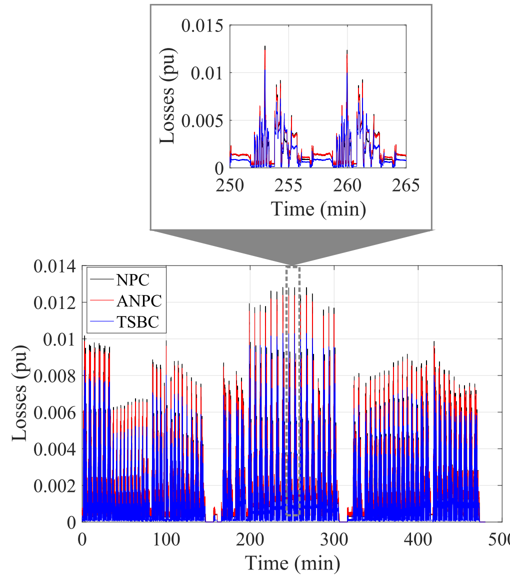

Fig. 9. Comparison of NPC, FT-ANPC and TSBC-MMC converters power losses considering the mission profile.

corresponds to a energy storage of $E_{nom} = 280kJ$. Therefore, the SM capacitance is given by [38]:

$$C = \frac{2E_{nom}}{9N{v_{sm}}^2} = 13mF. \quad (1)$$

Regarding arm inductances, the per unit (pu) values for grid connected converters typically are limited in the range of 0.3 pu [39]. This work employs $L_{arm} = 0.15pu$, in order to reduce the high order harmonics in circulating current. Therefore, $L_{arm} = 0.21mH$.

V. Losses and Cost Analysis

The comparison of the converter losses, following the mission profile is presented in Figure 9. The values are shown in pu, considering a base value of 7 MVA. As observed, the losses are smaller than 0.013 pu for all operation conditions. TSBC-MMC topology present smaller losses while FT-ANPC can have larger or smaller losses depending of the operating conditions.

The total power consumption of the power devices is evaluated considering the losses profile shown in Figure 9. The obtained energy losses are 77.57 kWh, 85.73 kWh and 60.80 kWh for the NPC, FT-ANPC and TSBC-MMC, respectively. As observed, the TSBC-MMC presents smaller consumption due to its lower switching frequency and the inherent lower losses of low voltage power modules.

The total cost of the solutions is strongly related with the redundancy strategies employed. For the NPC converter, it is considered a back-to-back backup converter, which is a common practice in industry [33]. The TSBC-MMC is designed with a redundancy factor of 10%. Additionally, there is no necessity to add redundancy for the FT-ANPC converter once it is a fault tolerant topology.

The initial cost is based on the number of components required and the price per part number. These estimates are only indicative and the real system costs may vary depending upon a variety of factors such as civil and engineering costs which cannot be evaluated [40]. An overview of the most important components that each configuration employs is shown in Table II.

TABLE II
Specifications of the converters.

Components	NPC	FT-ANPC	TSBC-MMC
IGBT modules	144	192	504
SM Capacitor kJ	282.24	188.16	616
Gate driver unit	144	192	504
Current sensor	18	12	30
Voltage sensor	12	8	66
Heatsink units	144	192	504
Mechanical Switch	-	6	63

The cost of the semiconductor devices, controls, cabinets is considered as 3.5 $/kVA of the installed switching power. The switching power P_s is given by [41]:

$$P_s = N_{semi} V_{block} I_{rated}, \quad (2)$$

where N_{semi} is the number of semiconductors, V_{block} is the rated blocking voltage of the devices and I_{rated} is the the rated device current. Additionally, the considered cost for the capacitors is 150 $/kJ [41].

Table III shows the estimated converter costs. As observed, the capacitors represents a small amount of the total cost (smaller than 1.6 % of total cost). For the presented case, the

FT-ANPC solution presents is 1.3 times more expensive than standard solution. For TSBC-MMC topology, the converter price is 3.7 times more expensive. The larger number of switches considerably increase the cost of the TSBC-MMC.

TABLE III
ESTIMATED COST OF THE INVERTERS.

Components	NPC	FT-ANPC	TSBC-MMC
Power Electronics	2,494,800 $	3,326,400 $	9,313,920 $
Capacitors	42,336 $	28,224 $	92,400 $
Total	2,537,136 $	3,354,624 $	9,406,320 $

VI. Decision Making

A system field failure of motor drive applications may be higher than a single system cost, which includes replacement free of charge, travel cost maintanance personnel, and penalty charges [33]. This fact underscores the importance of a thorough analysis during the choice and design of a converter for critical applications. The decision making of the methodology can be based on the relationship between investment capacity and metrics of reliability.

This work presents three solutions, each one with its particularities. The NPC converter with backup can overcome up to two failure situation in any element, independent of the failure mechanism. Maintanance time is required during the converter exchange. The option for FT-ANPC converter is 30% more expensive. However, each converter can survive up to four open-circuit failure situation in its power devices, totalling 16 specific failure events. The TBSC-MMC, is 3.7 time more expensive, yet it has greater flexibility of fault tolerance. It is able to overcome nine failure events, independent of the mechanism and element. Hence, the failure history can be another important parameter during the decision-making process.

VII. Conclusions

This work proposes a methodology of power converters selection and design for mission critical applications. As a case study it is adopted a rolling mill system from a big steel industry in southeastern Brazil. This methodology is detailed step-by-step, with the aim of field engineers being able to understand and repeat the process, in their specific areas of activity.

To demonstrate the methodology, two high-reliable alternatives were proposed to substitute the standard NPC solution: The FT-ANPC and the TBSC-MMC. The importance of DFR in mission critical applications was once again highlighted. The sizing of IGBTs power modules considering the real mission profile was demonstrated. Solutions to improve the reliability of system capacitors were suggested. The cost and losses analysis was chosen as a final selection criteria.

The decision making section was develop to highlight some important points during the system choice and design. Nevertheless, it is known that there are more complex decision-making processes and this can be better defined by the experts of the specific industry.

Acknowledgment

The authors would like to thank the financial support from CEFET-MG and the Brazilian federal government agencies CAPES and CNPq (research grant no. 459459/2014-7), and the Minas Gerais state government agency FAPEMIG.

References

[1] T. J. Hesla, “Electrification of a major steel mill part 5: Scherbius and kraemer drives [history],” *IEEE Industry Applications Magazine*, vol. 13, no. 4, pp. 8–11, July 2007.

[2] L. V. Nelson and E. L. Hough, “Interconnection of the 25-and 60-cycle system of the union electric light and power company,” *Transactions of the American Institute of Electrical Engineers*, vol. 51, no. 1, pp. 113–119, March 1932.

[3] A. A. Radionov, A. S. Maklakov, V. R. Gasiyarov, and E. A. Maklakova, “Research of electric drive at load impact on hot plate mill 5000,” in *2015 International Conference on Mechanical Engineering, Automation and Control Systems (MEACS)*, Dec 2015, pp. 1–4.

[4] E. A. Maklakova and V. R. Gasiyarov, “Impact load researches for different settings of current regulation loop of electric drive control system of rolling stand,” in *2016 Dynamics of Systems, Mechanisms and Machines (Dynamics)*, Nov 2016, pp. 1–4.

[5] S. Madhusoodhanan, K. Mainali, A. Tripathi, K. Vechalapu, and S. Bhattacharya, “Medium voltage (2.3 kv) high frequency three-phase two-level converter design and demonstration using 10 kv sic mosfets for high speed motor drive applications,” in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2016, pp. 1497–1504.

[6] E. Cengelci, P. N. Enjeti, and J. W. Gray, “A new modular motor-modular inverter concept for medium-voltage adjustable-speed-drive systems,” *IEEE Transactions on Industry Applications*, vol. 36, no. 3, pp. 786–796, May 2000.

[7] J. Dai, S. W. Nam, M. Pande, and G. Esmaeili, “Medium-voltage current-source converter drives for marine propulsion system using a dual-winding synchronous machine,” *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 3971–3976, Nov 2014.

[8] D. Krug, M. Malinowski, and S. Bernet, “Design and comparison of medium voltage multi-level converters for industry applications,” in *Conference Record of the 2004 IEEE Industry Applications Conference, 2004. 39th IAS Annual Meeting.*, vol. 2, 2004, pp. 781–790 vol.2.

[9] V. N. Ferreira, G. A. Mendonca, A. V. Rocha, R. S. Resende, and B. J. C. Filho, “Mission critical analysis and design of igbt-based power converters applied to mine hoist systems,” *IEEE Transactions on Industry Applications*, vol. PP, no. 99, pp. 1–1, 2017.

[10] V. N. Ferreira, G. A. Mendonça, A. V. Rocha, R. S. Resende, and B. J. C. Filho, “Proactive fault-tolerant igbt-based power converters for mission critical applications in mw range,” in *Applied Power Electronics Conference*, 2017.

[11] W. Kawamura, M. Hagiwara, H. Akagi, M. Tsukakoshi, R. Nakamura, and S. Kodama, “Ac-inductors design for a modular multilevel tsbc converter, and performance of a low-speed high-torque motor drive using the converter,” *IEEE Transactions on Industry Applications*, vol. PP, no. 99, pp. 1–1, 2017.

[12] F. Kammerer, J. Kolb, and M. Braun, “A novel cascaded vector control scheme for the modular multilevel matrix converter,” in *IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society*, Nov 2011, pp. 1097–1102.

[13] D. Andler, R. Álvarez, S. Bernet, and J. Rodríguez, “Experimental investigation of the commutations of a 3l-anpc phase leg using 4.5-kv;5.5-ka igcts,” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 11, pp. 4820–4830, Nov 2013.

[14] T. Bruckner, S. Bernet, and H. Guldner, “The active npc converter and its loss-balancing control,” *IEEE Transactions on Industrial Electronics*, vol. 52, no. 3, pp. 855–868, June 2005.

[15] D. Andler, R. Álvarez, S. Bernet, and J. Rodríguez, “Switching loss analysis of 4.5-kv;5.5-ka igcts within a 3l-anpc phase leg prototype,” *IEEE Transactions on Industry Applications*, vol. 50, no. 1, pp. 584–592, Jan 2014.

[16] H. W. van der Broeck, H. C. Skudelny, and G. V. Stanke, “Analysis and realization of a pulsewidth modulator based on voltage space vectors,” *IEEE Transactions on Industry Applications*, vol. 24, no. 1, pp. 142–150, Jan 1988.
[17] T. Bruckner, S. Bernet, and P. K. Steimer, “Feedforward loss control of three-level active npc converters,” *IEEE Transactions on Industry Applications*, vol. 43, no. 6, pp. 1588–1596, Nov 2007.
[18] S. Ogasawara and K. Akagi, “A vector control system using a neutral-point-clamped voltage source pwm inverter,” in *Conference Record of the 1991 IEEE Industry Applications Society Annual Meeting*, Sept 1991, pp. 422–427 vol.1.
[19] M. Liserre, A. Dell’Aquila, and F. Blaabjerg, “An overview of three-phase voltage source active rectifiers interfacing the utility,” in *2003 IEEE Bologna Power Tech Conference Proceedings,*, vol. 3, June 2003, pp. 8 pp. Vol.3–.
[20] Y. Okazaki, W. Kawamura, M. Hagiwara, H. Akagi, T. Ishida, M. Tsukakoshi, and R. Nakamura, “Experimental comparisons between modular multilevel dscc inverters and tsbc converters for medium-voltage motor drives,” *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 1805–1817, March 2017.
[21] W. Kawamura, M. Hagiwara, and H. Akagi, “Control and experiment of a modular multilevel cascade converter based on triple-star bridge cells,” *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3536–3548, Sept 2014.
[22] F. Z. Peng, J.-S. Lai, J. W. McKeever, and J. VanCoevering, “A multilevel voltage-source inverter with separate dc sources for static var generation,” *IEEE Transactions on Industry Applications*, vol. 32, no. 5, pp. 1130–1138, Sep 1996.
[23] B. Gemmell, J. Dorn, D. Retzmann, and D. Soerangr, “Prospects of multilevel vsc technologies for power transmission,” in *2008 IEEE/PES Transmission and Distribution Conference and Exposition*, April 2008, pp. 1–16.
[24] G. T. Son, H. J. Lee, T. S. Nam, Y. H. Chung, U. H. Lee, S. T. Baek, K. Hur, and J. W. Park, “Design and control of a modular multilevel hvdc converter with redundant power modules for noninterruptible energy transfer,” *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1611–1619, July 2012.
[25] M. Davies, M. Dommaschk, J. Dorn, J. Lang, D. Retzmann, and D. Soerangr, “Hvdc plus - basics and principle of operation,” SIEMENS, Tech. Rep., 2017.
[26] G. S. Konstantinou, M. Ciobotaru, and V. G. Agelidis, “Effect of redundant sub-module utilization on modular multilevel converters,” in *2012 IEEE International Conference on Industrial Technology*, March 2012, pp. 815–820.
[27] N. Ahmed, L. Ängquist, A. Antonopoulos, L. Harnefors, S. Norrga, and H. P. Nee, “Performance of the modular multilevel converter with redundant submodules,” in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Nov 2015, pp. 003 922–003 927.
[28] B. Li, Y. Zhang, R. Yang, R. Xu, D. Xu, and W. Wang, “Seamless transition control for modular multilevel converters when inserting a cold-reserve redundant submodule,” *IEEE Transactions on Power Electronics*, vol. 30, no. 8, pp. 4052–4057, Aug 2015.
[29] P. Hu, D. Jiang, Y. Zhou, Y. Liang, J. Guo, and Z. Lin, “Energy-balancing control strategy for modular multilevel converters under submodule fault conditions,” *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 5021–5030, Sept 2014.
[30] Y. Okazaki, H. Matsui, M. Hagiwara, and H. Akagi, “Research trends of modular multilevel cascade inverter (mmci-dscc)-based medium-voltage motor drives in a low-speed range,” in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, May 2014, pp. 1586–1593.
[31] D. W. Novotny and T. Lipo, *Vector Control ans Dynamics of ac Drives*. Clarendon Press, 1996.
[32] H. Wang, K. Ma, and F. Blaabjerg, “Design for reliability of power electronic systems,” in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, Oct 2012, pp. 33–44.
[33] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, “An industry-based survey of reliability in power electronic converters,” *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1441–1451, May 2011.
[34] *ABB Application note., “Load-cycling Capability of Hi-Pak IGBT Modules.”*.
[35] V. N. Ferreira, A. V. Rocha, and B. J. C. Filho, “Thermal degradation management in a fault-tolerant active npc converter,” in *2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC)*, Nov 2015, pp. 1–6.
[36] H. Wang and F. Blaabjerg, “Reliability of capacitors for dc-link applications in power electronic converters x2014;an overview,” *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3569–3578, Sept 2014.
[37] V. Najmi, J. Wang, R. Burgos, and D. Boroyevich, “High reliability capacitor bank design for modular multilevel converter in mv applications,” in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept 2014, pp. 1051–1058.
[38] K. Ilves, L. Bessegato, and S. Norrga, “Comparison of cascaded multilevel converter topologies for ac/ac conversion,” in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, May 2014, pp. 1087–1094.
[39] K. Sharifabadi, L. Harnefors, H. Nee, S. Norrga, and R. Teodorescu, *Design, Control and Application of Modular Multilevel Converters for HVDC Transmission Systems*. John Wiley & Sons, 2016.
[40] H. A. B. Siddique, A. R. Lakshminarasimhan, C. I. Odeh, and R. W. D. Doncker, “Comparison of modular multilevel and neutral-point-clamped converters for medium-voltage grid-connected applications,” in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, Nov 2016, pp. 297–304.
[41] S. P. Engel, M. Stieneker, N. Soltau, S. Rabiee, H. Stagge, and R. W. D. Doncker, “Comparison of the modular multilevel dc converter and the dual-active bridge converter for power conversion in hvdc and mvdc grids,” *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 124–137, Jan 2015.