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A Review of the Power Converter Interfaces for Switched Reluctance Machines

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Received: 1 June 2020; Accepted: 30 June 2020; Published: 6 July 2020

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Abstract: The use of power electronic converters is essential for the operation of Switched Reluctance Machines (SRMs). Many topologies and structures have been developed over the last years considering several specific applications for this kind of machine, improving the control strategies, performance range, fault-tolerant operation, among other aspects. Thus, due to the great importance of power electronic converters in such applications, this paper is focused on a detailed review of main structures and topologies for SRM drives. The proposed study is not limited to the classic two-level power converters topologies dedicated to the SRMs; it also presents a review about recent approaches, such as multilevel topologies and based on impedance source network. Moreover, this review is also focused on a new class of topologies associated to these machines, namely the ones with fault-tolerant capability. This new category of topologies has been a topic of research in recent years, being currently considered an area of great interest for future research work. An analysis, taking into consideration the main features of each structure and topology, was addressed in this review. A classification and comparison of the several structures and topologies for each kind of converter, considering modularity, boost capability, number of necessary switches and phases, integration in the machine design, control complexity, available voltage levels and fault-tolerant capability to different failure modes, is also presented. In this way, this review also includes a description of the presented solutions taking into consideration the reliability of the SRM drive.

Keywords: switched reluctance machine; SRM; topologies; multilevel; impedance source; fault tolerant

1. Introduction

The Switched Reluctance Machine (SRM) is an electric machine characterized by operating through a reluctance torque, generated by the interaction between the salient rotor poles and the energized stator poles. One important feature of this machine is that it does not require permanent magnets. Moreover, it is also characterized by a simple mechanical design. Regarding its reliability, since the design of the stator and rotor are simple, it is usually less subject to internal faults, presenting better fault-tolerant capability. This aspect can be considered one of the major advantages of this machine since it continues to operate even in the presence of shorted or disabled poles, although with increased torque ripple. The SRM, unlike induction machines, has a high independence among its phases. This independence guarantees the possibility of individual control in each of its phases. Additionally, the torque in this machine is a function of the phase square current and, because of this, the direction of the current is not important. Due to these important advantages this machine has been selected to be used in many applications, namely in the automobile industry [1–4], aerospace industry [5,6], appliance industry [7,8], energy storage systems [9–11], mining applications [12,13], industrial machinery [14–17], food processor compact drives [18–20], air conditioning systems [21,22], pumping systems [23–25] and renewable energy sources [26–28].

The use of an appropriate power electronic converter and control circuit are essential to accomplish the desired operation of the Switched Reluctance Machine (SRM). These devices, together with several sensors, conditioning circuits and other devices, compose an electric drive responsible to control the machine (SRM) currents and consequently the torque and speed. In this machine, due to the winding independence, it is possible to perform an independent current control in each phase, as a function of the rotor position. The theoretical current waveform of each phase is rectangular and, to provide such waveforms, it is necessary to use power converters able to impose bidirectional or zero voltages and control unidirectional currents in each phase. Such unidirectional currents are responsible for magnetizing, maintaining in a reference value and finally demagnetizing each phase. Thus, due to the importance of these power converters, many studies have been developed regarding the adopted topology and control system. To obtain the best operating performance of the SRM, the power converter topology must be carefully chosen. For example, the use of the conventional asymmetrical H-bridge topology (AHB) or other two-level converters are not always the best option. For many years, topologies with fixed two-level voltages have been the first option for power converters. Meanwhile, in the last years, new approaches were introduced to improve the performance of the SRM. For applications requiring wide range and high speed there are other options that allow an improved performance of this machine. Frequently, at high speed, the current cannot reach the defined reference value due to the electromotive force (EMF). Thus, instead of using a high DC voltage source, it is usually better to use a multilevel topology or an alternative topology with Boost capability. Another important aspect that emerged over the last years is the fault tolerant capability of power converters. In applications where safety is a main concern, AHB or other classical two-level converters are not the most appropriated, since they do not offer viable alternatives and the choice must therefore fall on other topologies with different characteristics.

This paper presents a comprehensive review of power electronic converters proposed to SRM applications, explaining operation principles, general characteristics and most important particularities. Considering the latest developments, a new classification is proposed (see Figure 1). According to this classification, power converters can be classified into two-level, multilevel, impedance source and fault-tolerant.

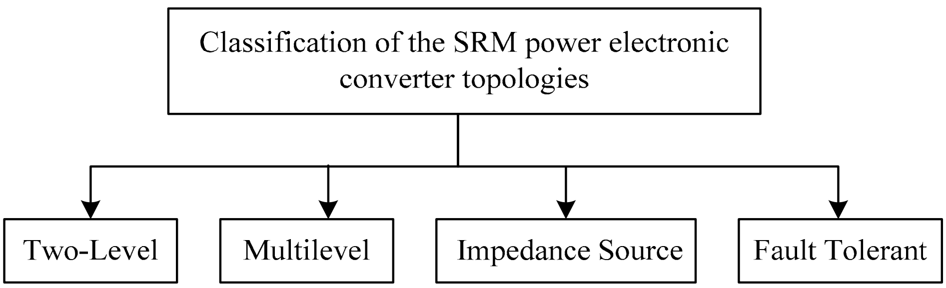


Figure 1. Classification of the Switched Reluctance Machine (SRM) power electronic converter topologies.

2. Two-Level Converters

The conventional SRM Power Converters can be classified, regarding its topologies, in two main groups: hard-switching (bridge, capacitive, magnetic, dissipative) and soft-switching converters (self-commutation) [29–32]. These converters are mainly characterized by generating two voltage levels for the magnetization or demagnetization of the machine winding. Among the hard-switching converters, the Bridge converters are the most common ones and four topologies are usually considered:

the asymmetrical half-bridge, the shared phase winding, the shared switch and the full-bridge (H-bridge). A more recent topology [33,34] that uses a conventional three-phase bridge converter (inverter) can also be considered as a Bridge converter. In turn, the Capacitive topologies usually include the C-Dump, the Sood, the Split DC and the Buck-Boost. The Magnetic topologies include the Bifilar and the Auxiliary Winding. For the Dissipative topologies, the most significant one is the R-Dump. A brief approach to all these topologies will follow.

2.1. A—Bridge Topologies

- Asymmetrical half-bridge (classical one)

The asymmetrical half-bridge topology [35–38], represented in Figure 2, uses 2n active switches, where n is the number of machine phases. It can operate in hard-switching (two operation modes) and soft-switching (three operation modes). Its main advantages are the independent control of the upper and lower switches, with great flexibility [39]; the use of all possible firing angles, allowing regenerative braking capability and the equal performance in both directions. The main disadvantages are the high number of power devices per phase; the possible problem with low voltage applications having two forward voltage drops; the relatively low demagnetization voltage at high speeds due to the fixed voltage supply; the need for a large capacitor on the supply voltage to filter the voltage ripple and the fact that demagnetization during generator operation mode with large currents could yield significant power losses through the diodes. This topology is one of the most used, with applications in many fields, such as automobile and aerospace industries and renewable energy sources.

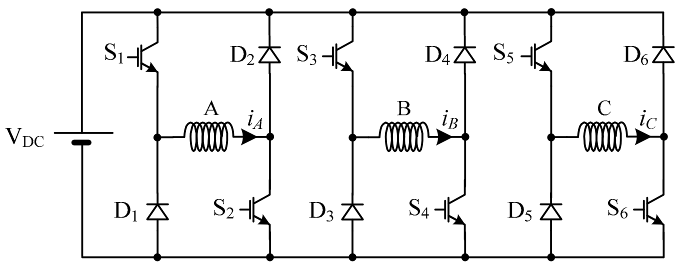


Figure 2. Asymmetrical half-bridge topology (AHB).

- Shared phase winding

The shared phase winding topology, represented in Figure 3, increases the utilization of power devices, increasing the correspondent duty cycle [29,40,41]. It requires an SRM with even number of phases, grouping together alternating windings in order to have an independent phase control. An SCR device is used in each phase, allowing the current in that phase. The main advantages of this topology are the use of only one power switch, one SCR and one diode per phase winding, the greater utilization of power switches, the possibility of having positive, negative and zero voltages, which means to have current control flexibility, and the possible independent control of phase current. The main disadvantages are the significant losses on SCR for high power applications, the SCR gate drive circuits that increases the costs and the complexity because of isolation need, the fact that current overlap is not possible in the same half bridge and the reduced fault tolerance. Thus, this topology is not recommended for high power applications.

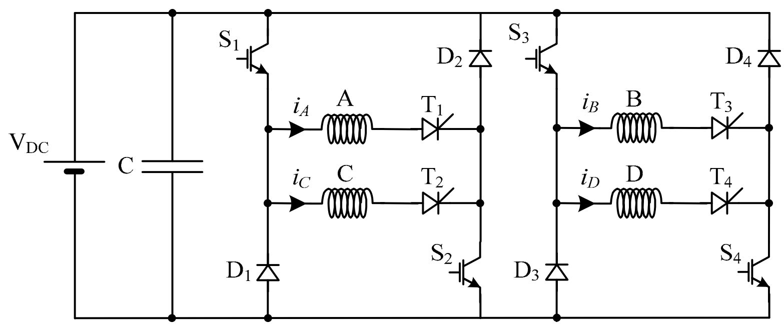


Figure 3. Shared phase winding topology.

- Shared switch (Miller converter)

In the shared switch topology, represented in Figure 4, switches and diodes are shared between more than one phase and there are many configurations for even and odd number of phases [42,43]. The main advantages of this topology are the reduced number of power devices and the possible independent phase control. The main disadvantages are that some phases cannot be turned on simultaneously, and when a change of direction is needed, the reference speed should be set to zero, with zero currents, and only after that it settles to a negative speed; in addition, care should be taken with mutual inductance that can cause excessive EMF and unwanted circulating currents and a reduced fault tolerance. Thus, there is a limited freedom of operation with this topology making it not recommended for some applications, like in the automotive industry.

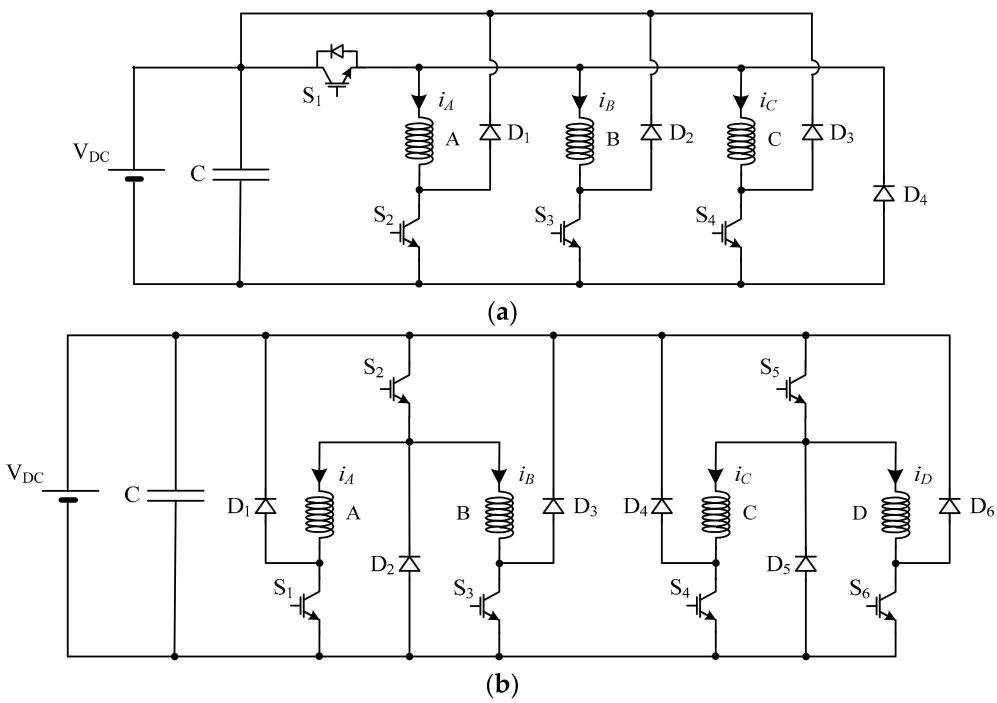


Figure 4. Shared switch topologies (**a**) per three phases, (**b**) per two phases.

- Full-bridge (H-bridge)

In the H-bridge topology, represented in Figure 5, the diodes are replaced by power switches, reducing the conduction and switching losses during freewheeling and demagnetization modes [44,45]. The main advantages are the greatest flexibility in motoring and generating modes and the improved operational efficiency during freewheeling and demagnetization modes. The main disadvantages are the underutilization of power switches and the additional cost for extra power switches and gate drive circuits.

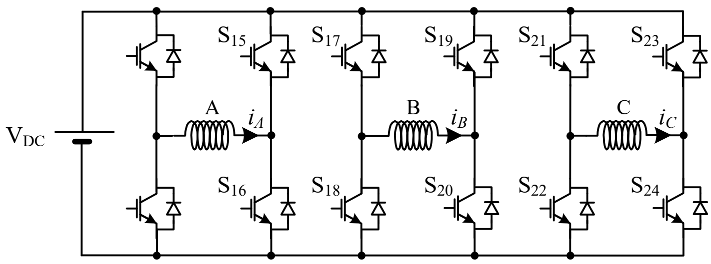


Figure 5. H-bridge topology.

- Conventional Three-Phase Bridge

In the conventional three-phase bridge topology, represented in Figure 6, a conventional three-phase inverter is used, connected to the windings that are connected in series, allowing a permanent circulating current [33,34]. The main advantage of this topology is the possibility of using a standard three-phase inverter, with no need of changing the internal structure of the machine or the excitation method. The main disadvantage is the complexity of the overall system, limited to three phases, if the advantage of a standard inverter is considered. Due to the limitation of the phases it is not recommended to be used in several applications, such as electric traction.

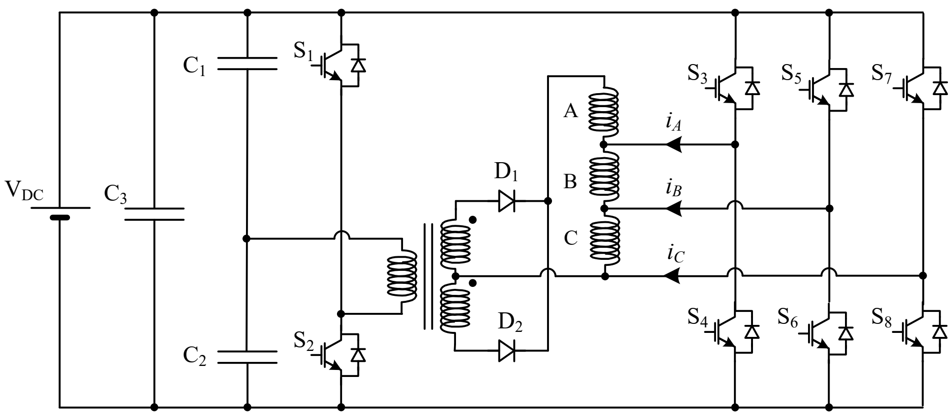


Figure 6. Conventional three-phase bridge topology.

2.2. B—Capacitive Topologies

In these topologies, energy freewheels into a capacitor at turn off. The additional capacitor is discharged by a later energization process.

- C-Dump

The C-Dump topology, represented in Figure 7, uses n + 1 switches, and thus, the freewheeling (demagnetization) circuit is shared by all the phases. This means that phase overlap control is possible and a minimum number of switches is used to obtain an independent phase control [46–48]. Mainly, three different operating modes can be considered: magnetization, freewheeling (with energy recovery) and demagnetization (with energy recovery). The main advantage is the ability to have independent phase control with a minimum number of switches. The main disadvantages are the limited demagnetization voltage (equal to the supply voltage minus the dump capacitor voltage), the additional losses that are experienced in the energy recovery circuit and the possibility of a bad situation if a failure occurs in the energy recovery circuit. Some of the mentioned disadvantages can be overcome by modifying the base topology [48]. The use of this topology should be limited to low speed applications. In this way, it is recommended to be used in applications like electric traction, renewable energy sources and energy storage.

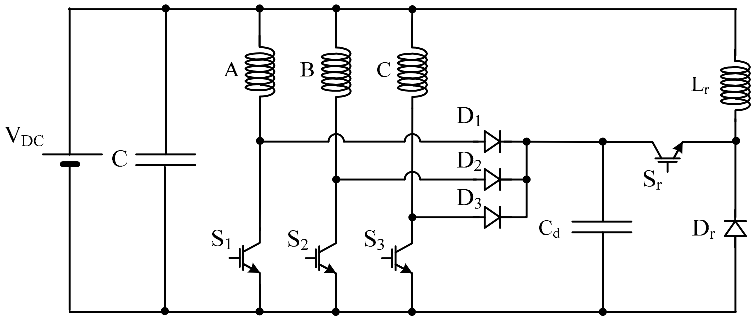


Figure 7. C-Dump topology.

- Sood

The Sood topology, represented in Figure 8, uses the boost capacitor as a dump capacitor. The topology is similar to the C-Dump topology but without the same features. It has two modes of magnetization: from the power supply or from the boost capacitor [29]. The main advantages of this topology are the lower number of required devices and the machine control freedom allowed by the four possible modes of operation. Its main disadvantages are the very complex control; the additional losses in the energy recovery circuit and the reduced fault tolerance. Regarding its applications, this topology presents similar limitations when compared with the previous converter. However, one of the applications which is extensively proposed is for pumping systems supplied by PV sources.

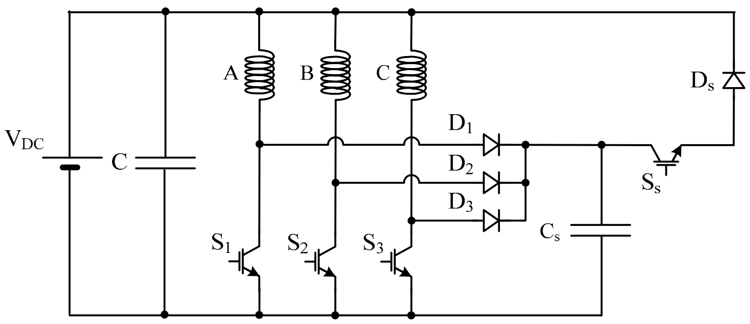


Figure 8. Sood topology.

- Split DC

The Split DC topology, represented in Figure 9, uses two series connected capacitors replacing the DC link capacitor [49–51]. It has only two modes of operation, magnetization and demagnetization, using only n switches. The main advantage of this topology is to use only one switch per phase, with no additional passive components. The main disadvantages are the requirement to balance the charge across the capacitors (needs to have an even number of phases), which results in some losses, the limitation of the supply voltage (only half) that is applied to the phase winding, resulting in a low dynamic response, and reducing the speed capability and the less fault tolerant capability. Thus, this topology is not suitable for some applications, such as the electric vehicle ones.

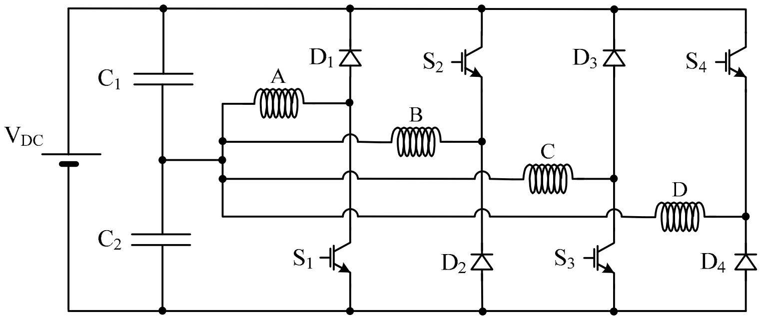


Figure 9. Split DC topology.

- Buck-Boost

The Buck-Boost topology, represented in Figure 10, uses a buck-boost front end stage offering extra flexibility for the SRM control by separating the magnetization and demagnetization voltages and offering a variable supply voltage [52]. The main advantages of this topology are the possibility of having an input voltage greater than the DC source voltage, particularly useful in the generator operating mode and for high speeds and the independent control of each phase with only one switch per phase. The main disadvantages are the complexity of the circuit and the higher voltage rating requirement for the power devices. Regarding the applications, this topology is particularly adapted to the electric vehicles and renewable sources.

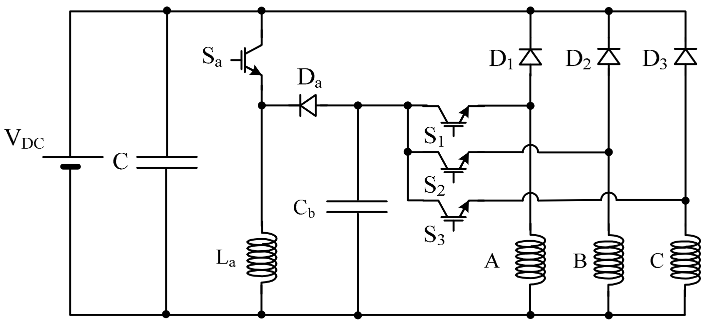


Figure 10. Buck-Boost topology.

2.3. C—Magnetic topologies

In these topologies, the energy stored in the phase winding magnetic field can be transferred to a coupled winding, which can be transferred to the energy supply or used in the magnetization of another winding [44].

- Bifilar

The Bifilar topology, represented in Figure 11, uses one switch per phase and has only magnetization and demagnetization operating modes [51], regenerating the winding magnetic energy to the source by coupled primary and secondary windings in a bifilar-wound SRM. The main advantage of this topology is the low number of switches. The main disadvantages are the machine cost, particularly for large machines; the reduced efficiency and the cost and complexity of the snubber circuits. Thus, this topology is not recommended for high power applications.

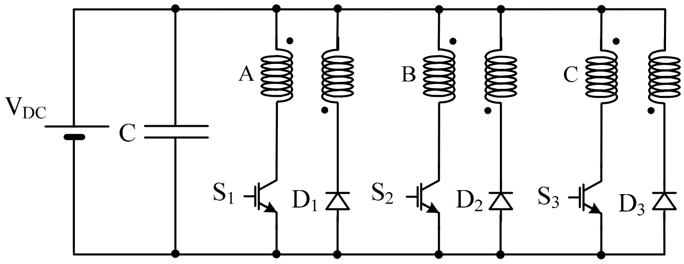


Figure 11. Bifilar topology.

- Auxiliary winding

The Auxiliary winding topology, represented in Figure 12, can have four operating modes: magnetization and freewheeling of the main winding and demagnetization of the main winding to the auxiliary winding and to the source. The main advantages are the increase of the system efficiency and performance by recovering the magnetic energy, the rapid increase of the phase winding current by the auxiliary winding stored energy and the possibility of soft-switching. The main disadvantage is the SRM extra cost [52]. Thus, like the previous one, this topology is not suitable for high power applications.

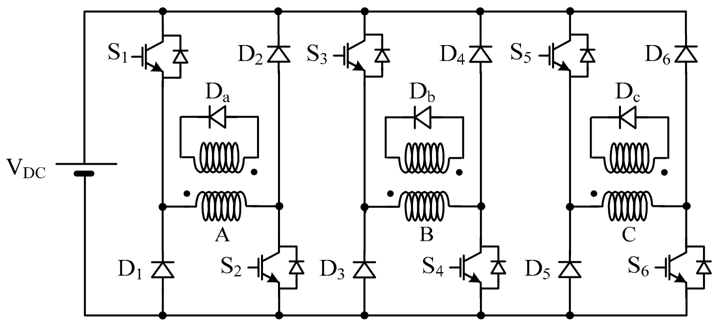


Figure 12. Auxiliary winding topology.

2.4. D—Dissipative Topologies

In these topologies, the energy, instead of being recovered, is dissipated in resistive charges. The structures are usually simple and the costs are relatively low [53].

- R-Dump

The R-Dump topology, represented in Figure 13, has one switch per phase and can only operate in hard-switching mode with two operating modes (magnetization and demagnetization) [53–56]. The main advantages of this topology are the simple structure, the low number of power devices and the low cost. The main disadvantages are the low efficiency and, consequently, the limitation for high power applications.

A comparative summary of the presented two-level power converter topologies can be seen in Table 1. The topologies are identified in the first column by the number of the figure. The topology characteristics that are highlighted in different columns are the numbers of switches, if the machine can have any number of windings, the control complexity, higher in the presence of extra elements that also should be controlled, e.g., capacitors, coils, snubbers or SCR elements, the fault tolerance capability and the need for a special machine design.

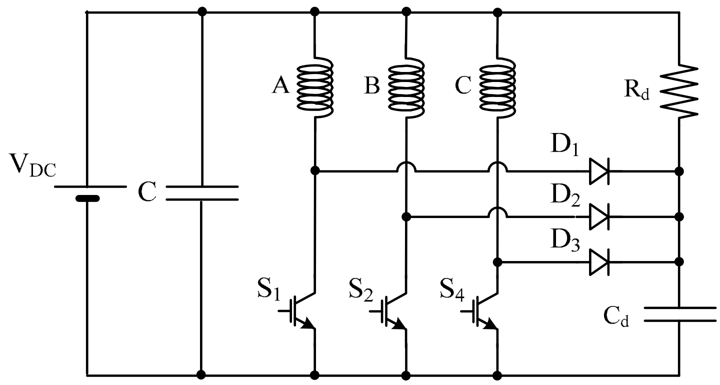


Figure 13. R-Dump topology.

Table 1. Comparative summary of the SRM two-level topologies.

Topology	N° of Switches	Designed for Any Number of Windings	Control Complexity	Fault Tolerance	Machine with Special Design
Figure 2 [35–38]	2/phase	Yes	Low	High	No
Figure 3 [29,40,41]	1/phase	No	Medium	Low	No
Figure 4a [42,43]	1/phase + 1	Yes	Low	Low	No
Figure 4b [42,43]	1,5/phase	Yes	Low	Low	No
Figure 5 [44,45]	4/phase	Yes	Medium	High	No
Figure 6 [33,34]	2/phase + 2	No	High	Low	No
Figure 7 [46–48]	1/phase + 1	Yes	Medium	Low	No
Figure 8 [29]	1/phase + 1	Yes	High	Low	No
Figure 9 [49–51]	1/phase	No	Medium	Low	No
Figure 10 [52]	1/phase + 1	Yes	High	Low	No
Figure 11 [51]	1/phase	Yes	High	High	Yes
Figure 12 [52]	2/phase	Yes	Medium	High	Yes
Figure 13 [53–56]	1/phase	Yes	Low	High	No

3. Multilevel Converters

Another approach under the point of view of the SRM power converter is to use topologies with capability to generate multilevel voltages. In this way, instead of having a single voltage level to magnetize or demagnetize the machine windings, these converters allow to apply several voltage levels. There are some advantages that can be achieved using these types of power converters in such machines. In fact, through the use of those converters, it is possible to improve the performance of the machine, reduce the power semiconductors switching frequency and give some more fault tolerant capability. In this way, several power converter topologies, developed specifically for the SRM, were proposed.

One of the multilevel converters, proposed for the SRM, was the Neutral Point Clamped Asymmetric Half-Bridge (NPC-AHB) [57–59]. This topology (Figure 14a) is an adaptation to the SRM of the classical NPC bridge converter. Thus, with this converter, it is possible to apply two voltage levels for the magnetization or demagnetization of the machine windings. This converter also allows some fault-tolerant capability. However, it is characterized by a high number of power semiconductors and requires DC voltage balance. Another topology, based on classic multilevel converters, is the asymmetric flying capacitor (Figure 14b) [59,60]. Like the previous topology, it requires a high number of power semiconductors and DC voltage balance. These two topologies are adequate to be applied to high power drives and especially in medium voltage applications since they allow to use power semiconductors with a reduced power ratio. In this way, it is indicated to be used in pumping systems with a very high capacity. It could also be used for electric vehicles, since in this case, a very wide range of speed variation is required. A topology based on classic cascaded H-bridge multilevel converter was also proposed [59,61,62]. As shown in Figure 14c, this topology uses cascaded asymmetrical H-bridges. However, besides the number of power semiconductors, it also requires several DC voltage sources. In this way, this topology is indicated to be used for decentralized battery energy storage system. A fourth topology, based on classical multilevel inverters, is the one based on the modular multilevel converter (MMC). Two solutions based on this structure were proposed. The first one is the classical asymmetric MMC [59]. In the second solution, the MMC structure is connected to the asymmetric bridge converter (Figure 14d) [63]. This converter was proposed to be used in the context of the decentralized battery energy storage system, by which each module is connected to a battery. It is also characterized by a high number of power switches.

Another topology that is a derivation of the multilevel T-Type inverter is the one presented in Figure 15 [64,65]. Since it is only required that the current flows in one direction, the topology was simplified with less fully controlled power semiconductors. As in the case of the NPC-AHB converter and Flying capacitor, this one also requires DC voltage balance. Comparing with those topologies the number of controlled power semiconductors is the same but regarding the number of diodes it requires a lower number.

Some derived topologies from the classical multilevel converters were also proposed. In [66], a NPC-AHB converter was proposed but with inherent dc-link voltage boosting capacitors. This topology was designed for the 8/6 SRM and it is characterized by the disconnection of the phases A and C with the phases B and D using power semiconductors (Figure 16a). Still, the boost capability is function of the capacitor value, being higher for low values. This converter was proposed to be used in high-speed electric vehicles applications. A modular structure based on an asymmetric half-bridge converter topology for an 8/6 SRM with a central-tapped winding node was proposed by [67] (Figure 16b). This structure was specially developed for electric and hybrid electric vehicles. It was designed for on-board DC and AC charging. Nevertheless, the multilevel operation is only achieved when the drive is connected to the AC grid.

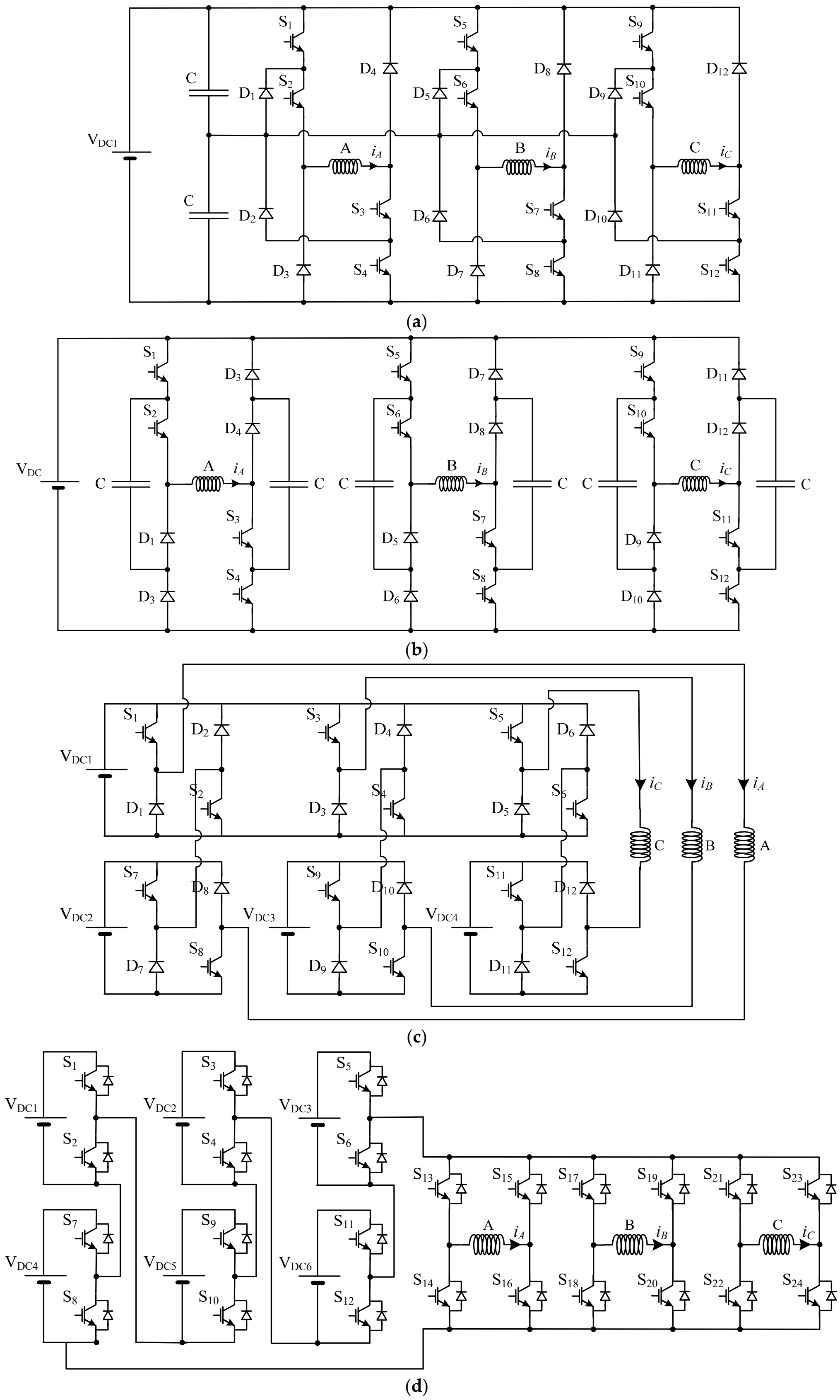


Figure 14. Multilevel converters based on classical topologies (**a**) NPC-AHB converter (**b**) Flying capacitor (**c**) cascaded asymmetrical H-bridge (**d**) modular multilevel converter (MMC).

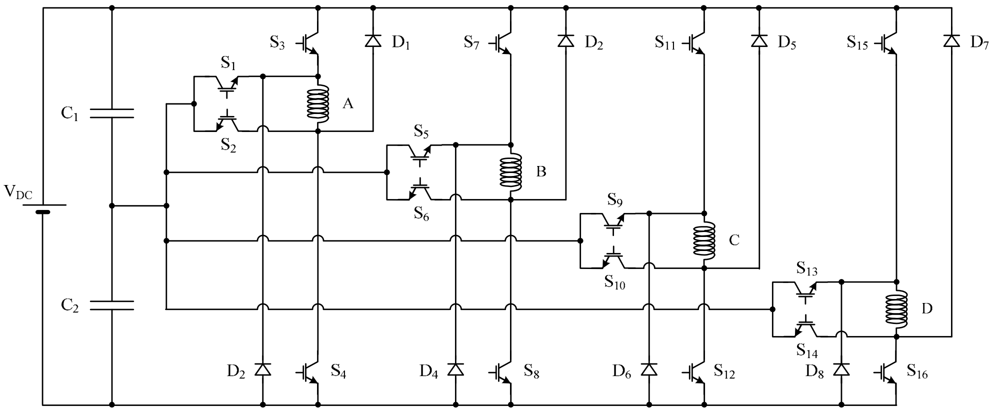
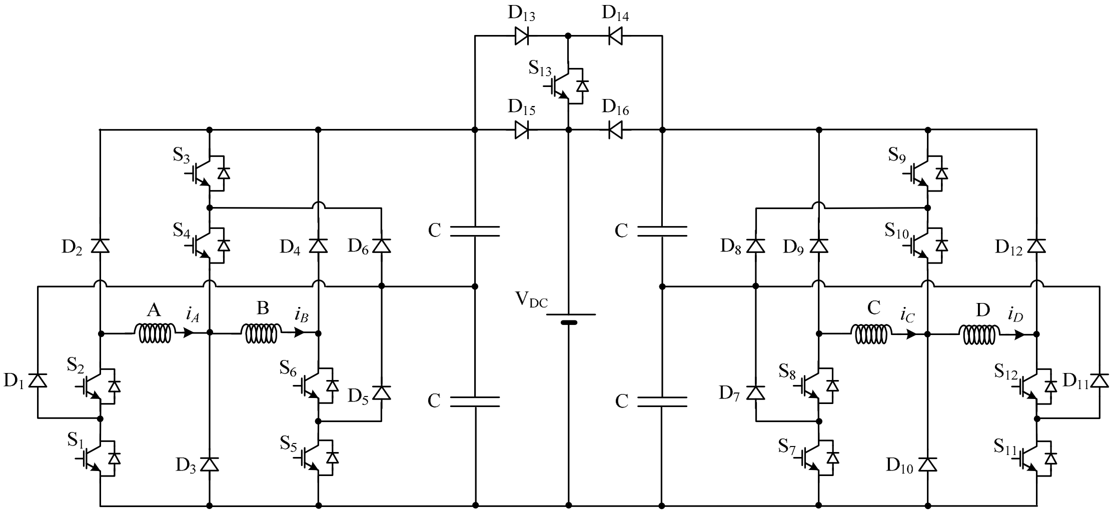
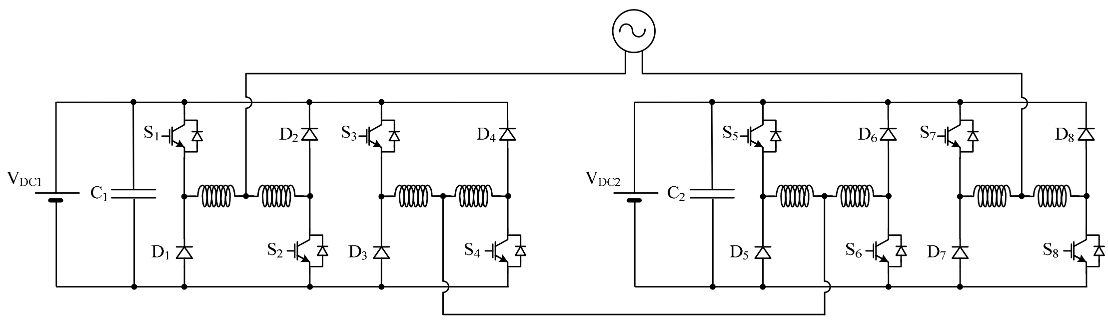


Figure 15. Multilevel converters based on classical topologies.



(**a**)



(**b**)

Figure 16. Derived converters from the classical multilevel topologies (**a**) with DC link capacitor voltage boosting (**b**) with a central-tapped node.

Topologies that are not based on the conventional multilevel converters have also been developed. Some of them have been designed with the purpose of reducing the number of power semiconductors. In this context, a topology that was an improvement of the asymmetric half-bridge converter, with the purpose to provide multilevel operation, is shown in Figure 17a [68]. Besides the possibility to generate multilevel voltages, it also allows to Boost the DC source voltage under dynamic operation. A similar structure, but adapted for the 8/6 SRM, was also proposed in [69] (Figure 17b). This topology was designed with the purpose of reducing the number of power semiconductors using a common leg for two of the windings. One of the problems of these topologies is that they require a more complex control system, namely to balance the floating capacitor. Another topology with boost capability, but in which symmetrical legs and common point for the machine windings were used, was also proposed (Figure 17c) [70]. This topology resulted in a high number of power switches, as well as the requirement of a complex control to balance the floating capacitor. These topologies have been proposed to be used in pumping systems associated to renewable sources such as PVs.

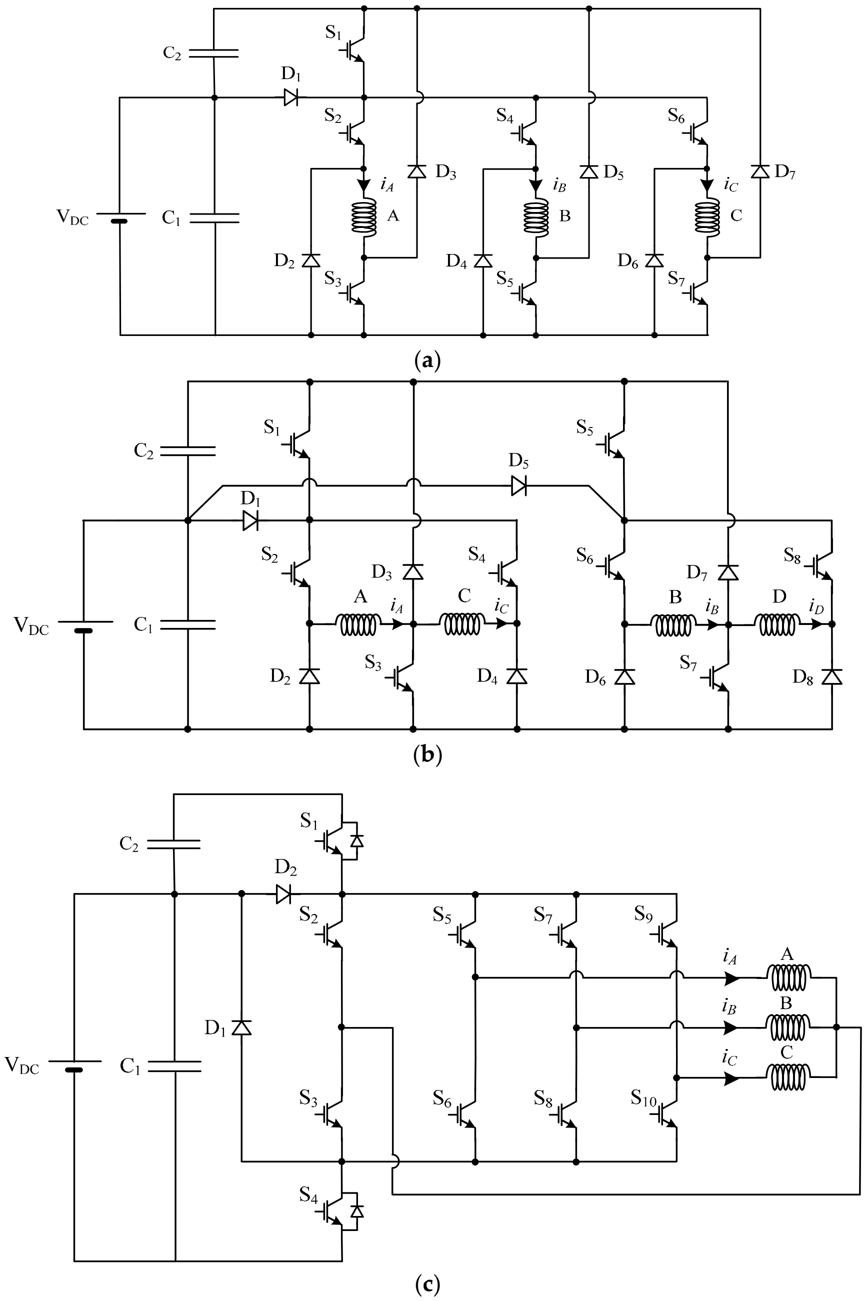


Figure 17. Multilevel converters based on an integrated boost circuit (**a**) with a classical AHBC (**b**) for 8/6 SRM with a common leg for two of the windings (**c**) with symmetrical legs and common point for the machine.

Multilevel topologies with reduced number of power semiconductors, but requiring two voltage sources, were also proposed. A topology in which switches connected to the middle point of the two DC voltage sources (T-Type) was proposed in [71], as presented in Figure 18a. This topology was designed for the 8/6 SRM, in which a common leg for two of the windings is used. Another topology, based on this structure, but with a minimized number of power semiconductors, was proposed in [72]. In fact, it only requires five switches for the 6/4 SRM (Figure 18b). These drives are indicated to be used in electric vehicles.

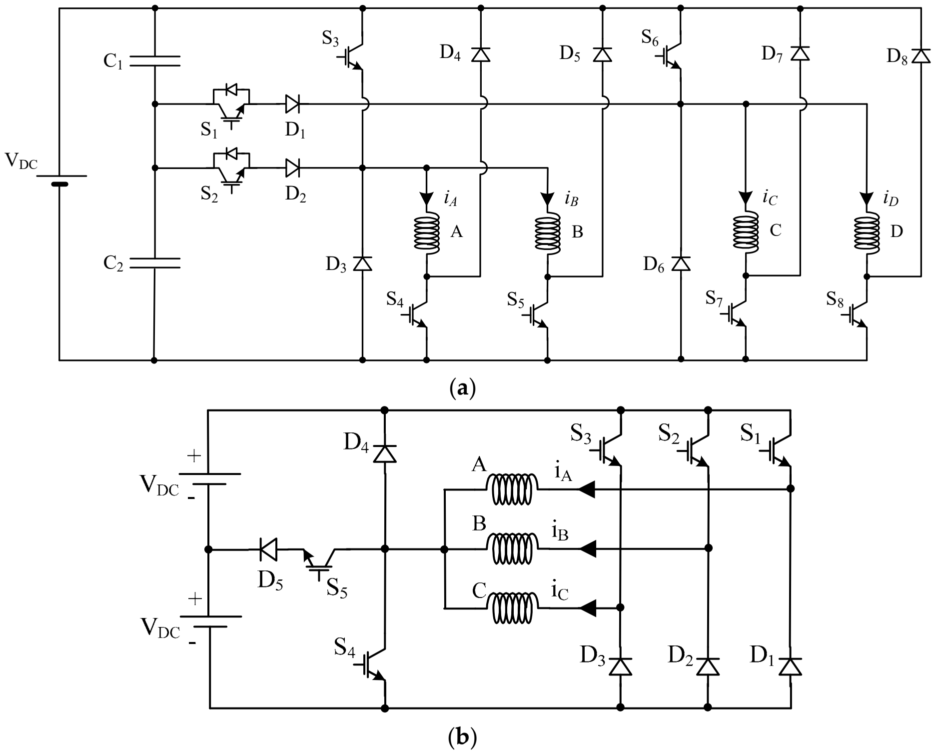


Figure 18. Multilevel converters based on two voltage sources (**a**) for an 8/6 SRM (**b**) for a generic SRM and common point of the machine.

A comparative summary of the presented multilevel power converter topologies can be seen in Table 2. In order to make this comparative study, the 8/6 SRM was considered for all topologies. Thus, from this analysis, the topologies that allow for modularity (increasing the number of levels through the integration of new classical converters) are the ones presented in Figure 14c,d. However, these topologies require a high number of switches and voltage sources. The topology of Figure 16b was developed for a machine with a special design, more specifically with a central-tapped winding node. There is also a limitation regarding the multilevel operation, since it only has this capability when it is in AC charging. Regarding the boost capability, only four topologies provide that (topologies of Figures 16a and 17a–c). Among them, the topology that requires a higher number of power switches is the one of Figure 16a and the one that requires a less number is the one of Figure 17b. Moreover, the topology that requires a smaller number of power switches is the one presented in Figure 18b, but does not have boost capability. This topology is also characterized by the requirement of a single voltage DC source. Regarding the control system, for the topologies of Figure 14a,b it could be necessary to enter into consideration with the balance of the capacitors voltage. Thus, this could introduce some extra complexity in the controller since in this case, it should not be designed only to control the machine. In the case of the topologies of Figure 14c,d, the controller must only be designed taking into consideration the machine, which means it can be considered the simplest, taking into account the power converter topologies. The power converter topologies of Figure 16a,b and Figure 17a–c are the ones that require the most complex control system. In the case of the topology of Figure 16a, the controller must also consider the intermediate dwell states. Different output voltage state sequences must be considered for different operating modes. In the case of Figure 16b topology, the controller must be designed in order to consider two modes of operation: motoring and regenerative breaking, associating them to the two converters. Regarding the topologies of Figure 17a–c an extra controller must be considered to ensure the balance of the floating capacitor. Because of that, an extra voltage sensor associated to the referred capacitor is also required.

Table 2. Comparative summary of the SRM multilevel topologies.

Topology	Converter Modularity	Boost Capability	N° of Switches (Machine with 4 Windings)	DC Voltage Sources	Designed for Any Number of Windings	Control Complexity	Machine with Special Design
Figure 14a [57–59]	No	No	16	1	Yes	Medium	No
Figure 14b [59,60]	No	No	16	1	Yes	Medium	No
Figure 14c [59,61,62]	Yes	No	16	5	Yes	Low	No
Figure 14d [59,63]	Yes	No	18	2	yes	Low	No
Figure 15 [64,65]	No	No	16	1	Yes	Medium	No
Figure 16a [66]	No	Yes	13	1	No	High	No
Figure 16b [67]	No	No	8	2	No	High	Yes
Figure 17a [68]	No	Yes	9	1	Yes	High	No
Figure 17b [69]	No	Yes	8	1	No	High	No
Figure 17c [70]	No	Yes	12	1	Yes	High	No
Figure 18a [71]	No	No	8	1	No	Medium	No
Figure 18b [72]	No	No	6	1	No	Medium	No

4. Converters Based on Impedance Source Network

Impedance source converters appeared with the purpose to overcome limitations of conventional topologies. These converters are characterized by the integration of specific impedance source networks. The main advantage of these converters is that they obtain a wider voltage gain. Due to the advantages that can be obtained with these converters, impedance source networks were also proposed to be used in the SRM drives [73,74]. Thus, a direct application of the network source (quasi-Z) into the SRM drive was proposed by [75,76]. This topology (Figure 19a) was proposed with the main objective to reduce the size of the capacitors in order to increase the reliability of the system. It was an improvement to the classical asymmetrical H-bridge with a bi-directional buck-Boost converter. However, this topology requires an extra leg with two transistors. Thus, in order to reduce the number of power semiconductors and simplify the topology, a new topology was proposed, being a derivation of the first one (Figure 19a) [77]. This reduction is obtained through the integration of the symmetrical leg in the legs that control the SRM windings. Thus, this topology will only require six switches and diodes for the 6/4 SRM (Figure 19b). Due to their capability of wide voltage range gain these topologies are indicated to systems that require wide speed range operation. These topologies were proposed to be used in electric vehicles and also in pumping systems associated to renewable sources such as PVs.

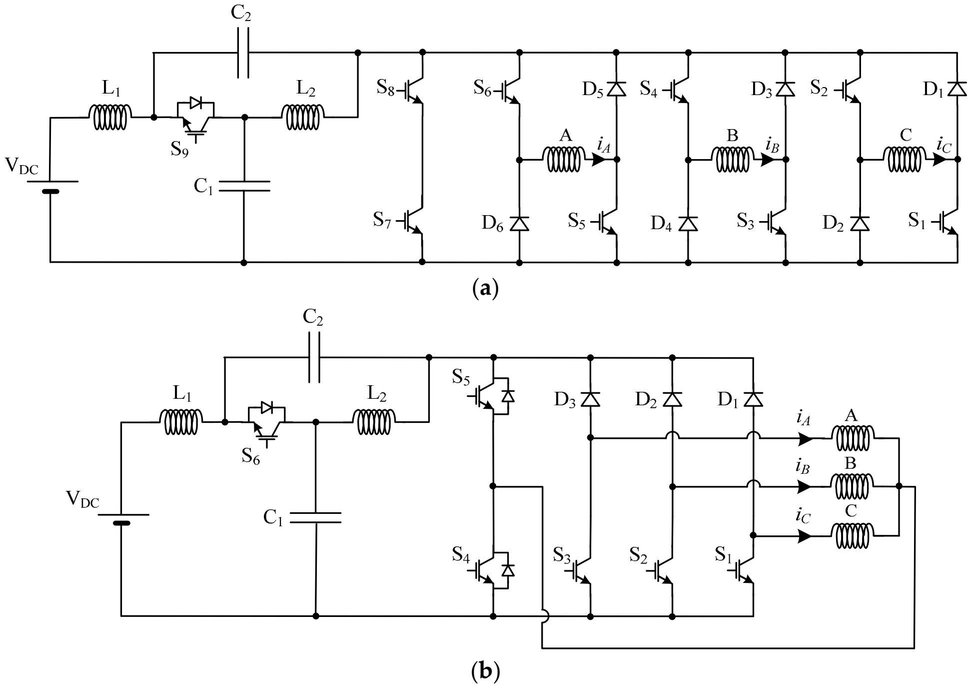


Figure 19. Converters based on the impedance source network (**a**) with extra symmetrical leg (**b**) integration of the symmetrical leg in the legs that control the SRM windings.

A topology with a modified quasi-Z source converter was proposed with the objective to decouple the magnetizing and demagnetizing port [78]. As shown in Figure 20, the magnetizing port is connected to the capacitor C1 of the quasi-Z network while the output terminal of this network is connected to the demagnetizing port. With this disconnection the current overlap of the SRM subsequent phases is avoided. Another particularity is that a reduction in the torque ripple was verified. However, the switch used to control the shoot-through state is not integrated in the legs that control the current of the SRM windings. This results in an increase of the number of switches. Since this topology presents the same characteristics of the previous ones, its possible applications are the same.

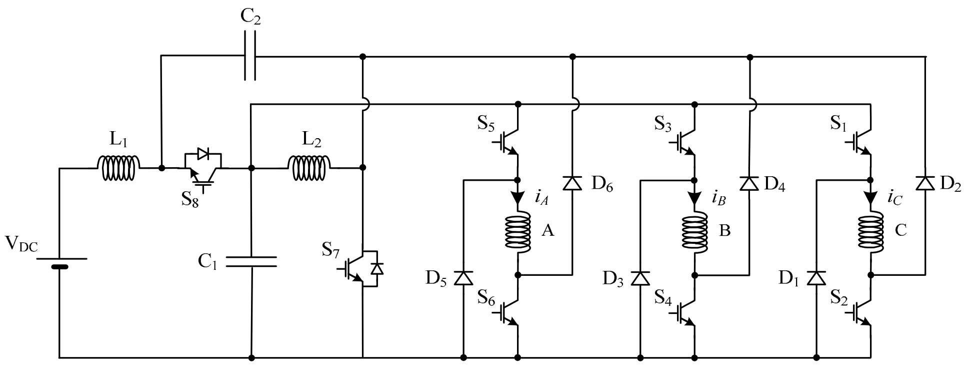


Figure 20. Converter with a modified quasi-Z network.

The quasi-Z impedance source network was also integrated in the SRM drive, but in a way that also allows to operate as a multilevel converter. In Figure 21a the topology proposed by [79] is presented, in which it is possible to see that the magnetizing process can be done through two different terminals of the quasi-Z network ensuring the multilevel operation. The switch connected to the lower terminal voltage can also be used to demagnetize; therefore, it is also possible to provide a multilevel operation during the demagnetization process. Nevertheless, the difference between the voltage levels cannot be independently regulated. To overcome this limitation, a derived topology was proposed [79]. In this topology, one of the voltage levels is fixed and equal to the DC voltage source and the other one is regulated, as shown in Figure 21b. This new configuration does not require extra power semiconductors, and maintains the possibility to generate five voltage levels. As in the previous solutions, this topology is also indicated to be used for electric vehicles and pumping systems with renewable sources.

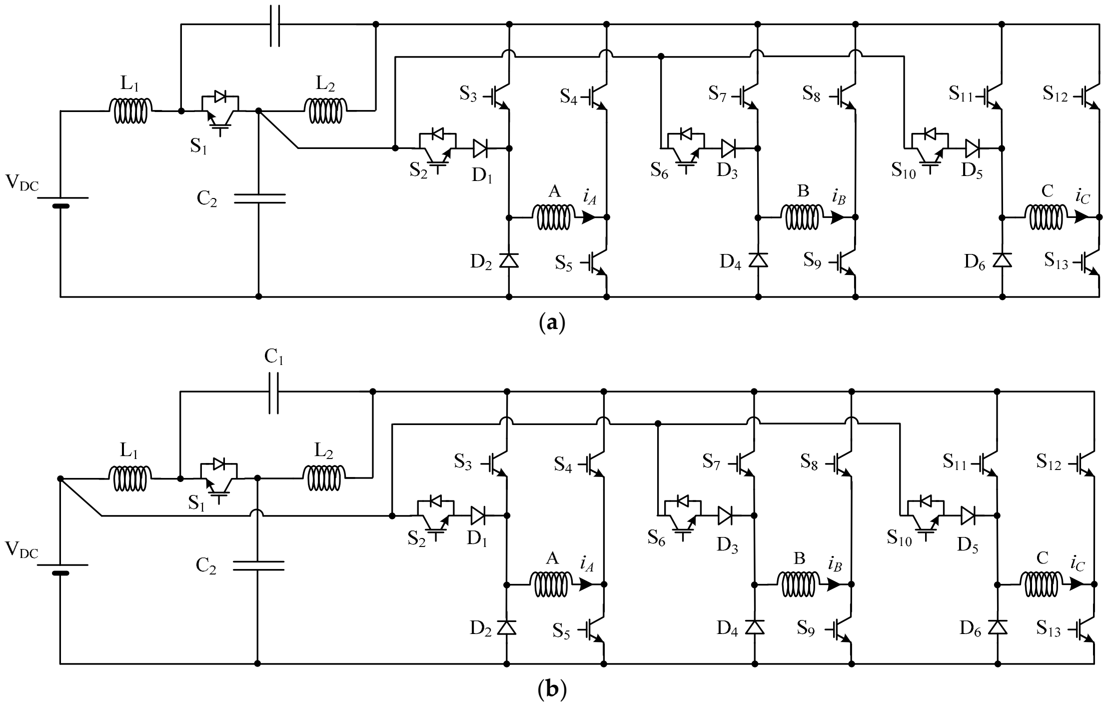


Figure 21. Converters based on the impedance source network with multilevel capability (**a**) with fixed asymmetrical voltages (**b**) with variable asymmetrical voltages.

To verify the different characteristics of the several presented impedance source converter topologies, a comparative summary is presented in Table 3. Since all topologies can be applied to any SRM, for this comparative study it was considered that all topologies are for the 6/4 machine. Thus, regarding the number of switches, the topology of Figure 19b is the one that requires fewer numbers. However, this topology does not have capabilities regarding the decoupling of the magnetization and demagnetization port, multilevel operation and capacitors with reduced size. From the point of view of the multilevel operation, only topologies of Figure 21a,b fulfill that criterion. They also allow for decouple of magnetization and demagnetization port. However, those topologies are the ones that require more switches. Regarding the possibility to use capacitors with reduced size, only the topology of Figure 20 fulfills that criterion. Moreover, it also allows for decouple of magnetization and demagnetization port.

Table 3. Comparative summary of the SRM impedance source converters.

Topology	N° of Switches	Decouple of Magnetization and Demagnetization Port	Multilevel Operation Capability	Capacitors with Reduced Size
Figure 19a [75,76]	9	No	No	No
Figure 19b [77]	6	No	No	No
Figure 20 [78]	8	Yes	No	Yes
Figure 21a [79]	13	Yes	Yes	No
Figure 21b [79]	13	Yes	Yes	No

5. Converters with Fault-Tolerant Capability

Fault-tolerant capability of power electronic converters is, in general, an ambition in most applications. It is usually desirable for applications to proceed in operation (fully or in a degraded mode) in the event of one or more failures until the next opportunity for maintenance and eventual repair. Each application has different requirements regarding fault tolerance in the energy processing stage, but the problem assumes special importance in safety critical applications or in highly sensitive equipment.

Several research papers have been published concerning different fault-tolerant aspects of power converters particularly the voltage source inverter (VSI) since it is one of the most common topologies adopted in industrial and commercial equipment for speed control, e.g., [80–83]. The problem of converter failures is an extensive and complex subject. Within the power stage, besides the electrolytic capacitors, the power semiconductors and their control electronics are considered the main cause of faults. Usually, the main failure modes that compromise the operation of power converters are: DC link capacitor failure, transistor open-circuit, transistor short-circuit, freewheeling diode open-circuit and freewheeling diode short-circuit [82–86].

In general, reliability improvements of power electronic converters may be achieved in different ways, e.g., by providing overrated or more reliable components, by using redundant design, or adopting automatic changes in the control strategy. These can be used either individually or in combination.

Because SRM power converters share the same type of power semiconductors with other types of electric drives, the failure modes are essentially the same. Nevertheless, fault-tolerant techniques used in SRM power converters cannot be adopted in the same way. Firstly, the SRM has basically no physical connection between phases (as opposed to AC machines) and an independent control can be provided. Secondly, SRM is characterized as a fault-tolerant machine, especially when the number of phases is equal to or greater than four, allowing to explore the possibility to operate with fewer phases due to controlled power semiconductors failure (or winding failure) and still providing starting torque on the expense of torque quality. Additionally, due to the physical separation between phases, most common topologies for SRM drives only make use of one controlled power semiconductor in the same branch (or leg), unlike two-level VSIs used in AC drives which have at least two. Due to these features, it is possible to disconnect permanently other controlled power semiconductor of the same phase to stop propagating the effect of short-circuit faults, which are usually very catastrophic, producing braking torque and high degradation of system performance. After current extinction, the system operation is similar to an open-circuit fault in the SRM phase. Additionally, the use of one controlled power semiconductor in the same branch avoids short-circuits in the DC bus.

An extended review of fault-tolerant power converters for SRM drives is presented in this section considering three different approaches. Firstly, power converter structures combining controlled power semiconductors and static (or mechanical) switches. Secondly, power converter structures based only on power semiconductors. In these two approaches, the machine structure remains unchanged and the achieved fault-tolerant operation (fully or degraded) is only due to modifications in the power converter and control strategy. Finally, some fault-tolerant methods are introduced based on modified power electronic converter combined with increased number of phases, central-tapped or split windings. In some of the articles presented next, the detection and diagnosis methods are not mentioned, but their use is implicit. This and other aspects of fault-tolerant topologies are presented in this section.

5.1. Power Converters with Controlled Power Semiconductors and Static (or Mechanical) Switches

Power converters combining controlled power semiconductors and static (or mechanical) switches are reviewed in this subsection. Most converters of this kind can provide full fault-tolerant operation after an open-circuit or short-circuit failure mode in one (or more) controlled power semiconductor. The use of static (or mechanic) switches allow to isolate and replace faulty switches or branches by similar standby redundant devices and restore the normal operation in most situations. Despite this, there are also converter topologies of this kind where the desired fault-tolerant operation is not fully achieved.

Figure 22 presents the topology proposed by [87]. In this topology, two additional controlled power semiconductors and six thyristors are used as complement of the classic AHB. The upper switch SA and the three thyristors T1, T2 and T3 tolerate the upper switch faults, while the lower switch SB and the three thyristors T4, T5 and T6 tolerate the lower switch faults. The proposed fault-tolerant strategy is based on switching the additional thyristors to bypass the faulty part. If the thyristor SA or SB is shared by one phase due to single open-circuit failure mode, the phase current at fault-tolerant operation is the same as healthy conditions. If more than one phase share SA or SB (like two upper open-circuit failures), the converter performance is different from healthy conditions. Because thyristors are semi-controlled switches and do not switch off until both faulty phases have negative voltage simultaneously, the demagnetization process in one of the faulty phases is hard to achieve, particularly at high speeds when voltage modulation control is used. This leads to degraded operation in the system performance. Short-circuit failures in controlled power semiconductors are not covered by this topology.

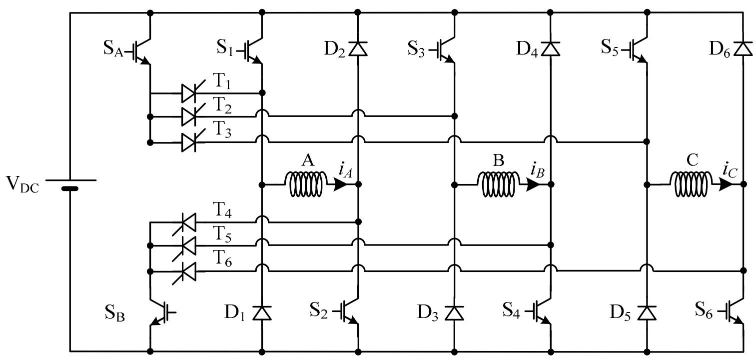
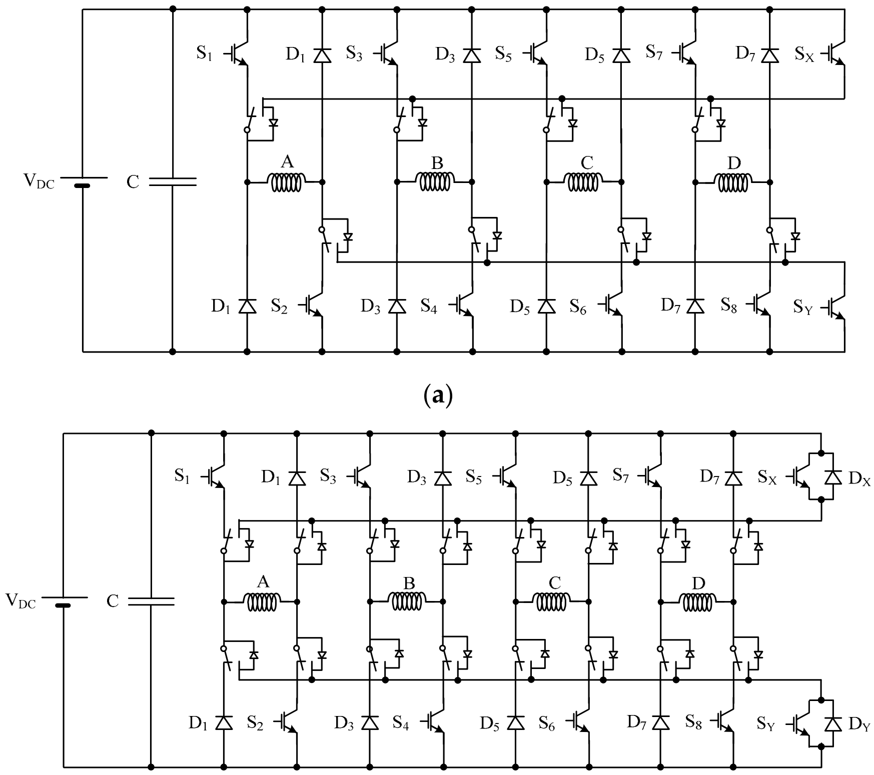


Figure 22. Fault-tolerant topology proposed by [87], combining the classic AHB with two additional controlled power semiconductors and six thyristors.

Two topologies with full fault-tolerant design are proposed by [88] as presented in Figure 23. In these topologies, a group of mechanical switches and auxiliary diodes and two additional controlled power semiconductors are used to isolate and replace faulty power devices independently of the failure mode. Auxiliary diodes are used to launch immediately the redundant controlled power semiconductors, which will be short-circuited after the switching operation, avoiding additional losses. Figure 23a shows the solution for one standby redundant switch to four in operation considering a four-phases SRM. The solution presented in Figure 23b allows to isolate and replace not only the controlled power semiconductors, but also the freewheeling diodes. The main disadvantage of the proposed solutions is the necessary number of mechanical switches and auxiliary diodes to achieve the full fault-tolerant design. These solutions can be applied to any SRM independently of the number of phases.



(**b**)

Figure 23. Fault-tolerant topologies proposed by [88]. Solution for isolate and replace the faulty controlled power semiconductor (**a**) and faulty controlled power semiconductor and freewheeling diode simultaneously (**b**).

Another topology with fault-tolerant design was proposed by [89] as presented in Figure 24. This topology uses a standby single-phase full bridge combined with an additional group of mechanical switches to replace up to four (two upper and two lower) faulty active switches. The proposed structure allows to replace up to four open-circuit faulty controlled power semiconductors considering the classic AHB topology for three-phase SRM. Despite the number of mechanical switches, this solution is not able to isolate short-circuit failures in controlled power semiconductors. Since no other isolation or control strategies are presented to deal with this fault, fault tolerance to short-circuit failures seems to be impractical.

Another fault-tolerant topology was introduced by [90], which depends on using a healthy leg to control two phases not in sequence like phases 'A' and 'C' or phases 'B' and 'D' in a four-phase SRM and considering the classic AHB topology. This solution takes advantage of the independence between SRM phases and requires static switches (e.g., S_1, S_2, ...) connected between phases not in sequence. An example of the proposed solution can be seen in Figure 25, connecting phase 'A' to phase 'C.' The proposed solution is infeasible for SRMs with an odd number of phases and only the open-circuit failure modes of controlled power semiconductors are considered.

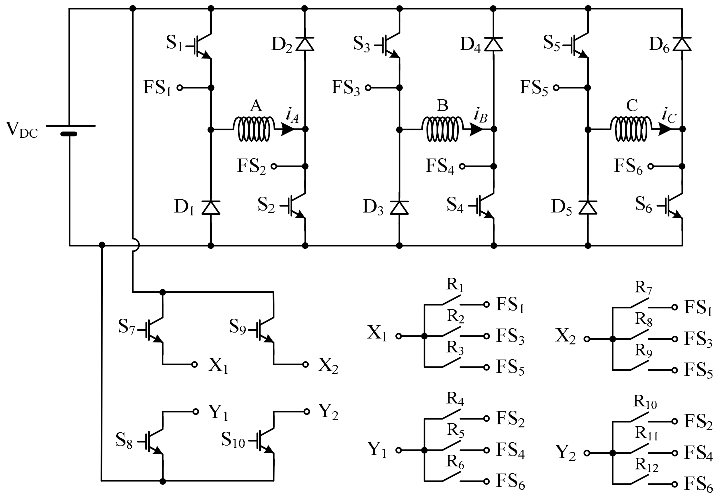


Figure 24. Fault-tolerant topology proposed by [89]. Solution using a standby single-phase full bridge of controlled power semiconductors combined with additional mechanical switches to replace up to four (two upper and two lower) faulty active switches.

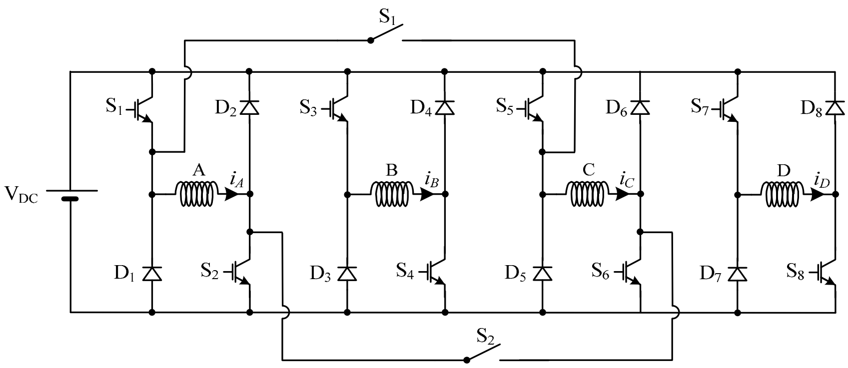


Figure 25. Fault-tolerant topology proposed by [90] using a healthy leg to control two phases not in sequence. This solution requires static switches to establish the connection between phases.

The proposed solution, presented in [91], uses the same principle of [90] with some improvements regarding fault-tolerant operation. This solution also depends on using healthy legs to control two phases not in sequence, such as phases ‘A’ and ‘C’ or phases ‘B’ and ‘D,’ in a four-phase SRM, but it uses several changeover solid-state relays (SSRs) to connect the faulty legs to other healthy phase in order to replace and isolate the faulty devices. The advantage of this solution is the ability to isolate faulty controlled power semiconductors regardless of the failure mode (open-or short-circuit). The main disadvantage is the necessary number of solid-state relays (SSRs) to perform this operation. This solution is also infeasible for SRMs with an odd number of phases. An example of this solution can be seen in Figure 26.

Another fault-tolerant topology was introduced by [92] which provides a solution for both the open- and short-circuit faults in controlled power semiconductors of the SRM converter. The proposed converter is composed of two standard six-pack switch modules. Under normal conditions, bidirectional current excitation is developed in the proposed converter, where all the controlled power semiconductors are actively involved. Under switch open-circuit faults, the faulty phase is adjusted to unidirectional current excitation without degrading the machine performance. Under switch short-circuit faults, the machine can still work steadily with a single six-switch inverter module by easily reconstructing the proposed converter opening the relays K1–K4 (depending on the faulty controlled power semiconductor). In order to implement the proposed tolerance strategy to short-circuit faults, all the upper (or lower, depending on the exact fault location) switches belonging to the same faulty inverter module must be turned on to connect the machine windings in star. Figure 27 illustrates this fault-tolerant topology.

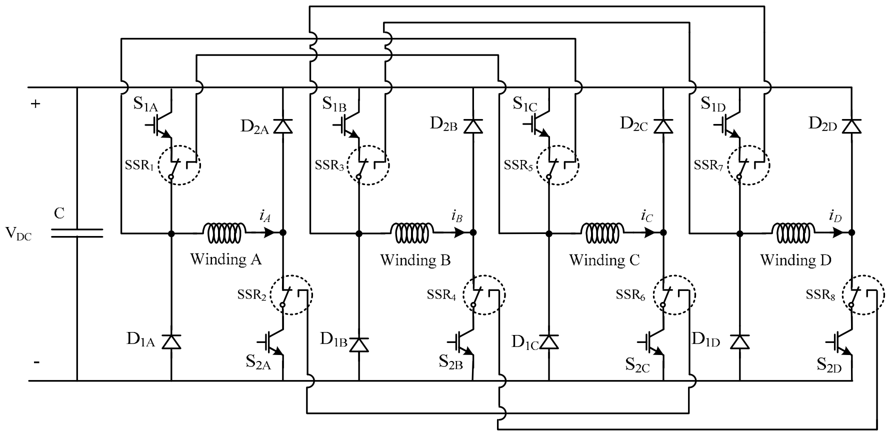


Figure 26. Fault-tolerant topology proposed by [91] using a healthy leg to control two phases not in sequence. This solution requires several solid-state relays (SSRs) to connect the faulty legs to other healthy phase in order to replace and isolate the faulty power semiconductors.

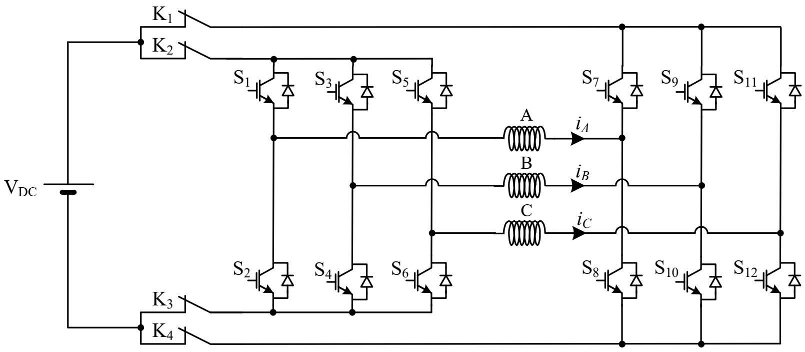


Figure 27. Fault-tolerant topology proposed by [92] using two standard six-pack switch modules and isolation relays (mechanical switches) to isolate short-circuit failures in controlled power semiconductors. Both open- and short-circuit failure modes are covered in this topology.

5.2. Solutions Using Only Controlled Power Semiconductors

Power converters using only controlled power semiconductors without any auxiliary devices are reviewed in this subsection. The number of proposed solutions of this kind is reduced and most power converters using only additional controlled power semiconductors cannot provide full fault-tolerant operation after an open-circuit or short-circuit failure. In this situation, there are several SRM multilevel topologies already described in Section 3.

In [58], a study about the use of a NPC-AHB converter regarding their capability to provide fault tolerance was presented. However, there are several faults in which that capability is not achieved. For example, in case of an open-circuit failure of outer power devices (see Figure 14a) some essential voltage levels are lost (+V_{DC} or $-V_{DC}$). Despite this, the three-phase SRM is still able to operate, although with speed and torque degradation. Short-circuit failures in controlled power semiconductors are not covered by this topology.

Another fault-tolerant topology of this kind was introduced by [93]. The solution presented in this research paper allows a full fault-tolerant operation regarding different failure modes in controlled power semiconductors. Both open- and short-circuit failures in controlled power semiconductors are covered by this topology. In some cases, multiple failures are allowed. The proposed solution takes advantage of multilevel voltages and bidirectional current excitation of the SRM, which, when associated to a specific control strategy, can provide the desired fault-tolerant operation. The most undesirable failures within this fault-tolerant multilevel converter are the short-circuits in outer controlled power semiconductors. Under these failures the machine windings can still be controlled through other switches but intermediate voltages (+V_{DC} /2 or $-V_{DC}$/2) cannot be used. Due to this, the switching frequency of the phase under fault will increase. One of the main disadvantages of the proposed solution is the high number of controlled power semiconductors necessary to achieve fault-tolerant operation. The proposed solution can be seen in Figure 28.

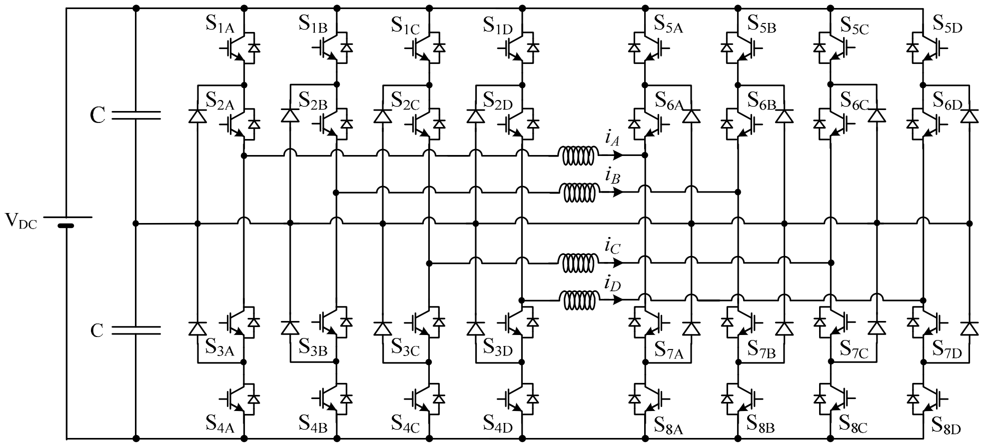


Figure 28. Fault-tolerant multilevel topology proposed by [93], combining multilevel operation, bidirectional current excitation of SRMs and changes in the control strategy. Both open- and short-circuit failures in controlled power semiconductors are covered by this topology.

5.3. Solutions Combining Modified Converters and Modified SRMs

Solutions combining modified power electronic converter structures and modified SRMs structures are reviewed in this subsection. In general, the proposed solutions take advantage from the fault-tolerant characteristics of SRMs. Unlike AC drives, in which the three-phase currents are connected and linked, the magnetic independence between phases and independent control of SRMs allow to minimize the effect on speed and torque, especially when the number of phases is equal to or greater than four. In fact, the four-phase SRM can run as a three-phase machine and provide a starting torque on the expense of torque quality, while the three-phase SRM during one phase failure can continue operation but cannot provide a starting torque.

The fault-tolerant solution introduced by [94] combines a classic AHB topology and a classic redundant VSI topology applied to a three-phase SRM. The redundant three-phase VSI is connected to each central-tapped winding phases and the whole circuit is divided into two parts: a left part and right part, as shown in Figure 29. Each part has the same components, including diode and switching device. The SRM phase winding was also designed to have axial symmetry characteristic to be employed in fault-tolerant operation. In normal conditions, the proposed solution works only with the classic AHB topology. The classic redundant VSI topology works only at fault condition combined with the classic AHB. When an open-circuit fault occurs, for example in S_1, the half bridge (S_7 and S_8) is activated to combine with the right part of the converter to form a new fault-tolerant topology, isolating the faulty switch. When a short-circuit fault is detected, for example if S_1 has a short-circuit fault, S_7 is enabled by giving drive signals to replace S_1. In this situation the right part of the converter and half bridge compose a new asymmetrical half bridge. In order to block the faulty part, switching device S_2 is employed as chopping device. In excitation and freewheeling state, due to S_7 conducting, both sides of phase winding L_{A1} share the same electric potential that prevent the current forming in L_{A1}, bypassing the short-circuited switch to stop propagating the effect of this fault. The control strategy adopted in this fault-tolerant solution uses closed-loop current control under normal and faulty conditions, combined with adjustments in the turn-on and turn-off angles to reduce the torque ripple due to faulty devices. The system performance of the proposed solution, under faulty operation, is quite similar to normal operation. The only difference is the current slope in faulty phases due to missing winding.

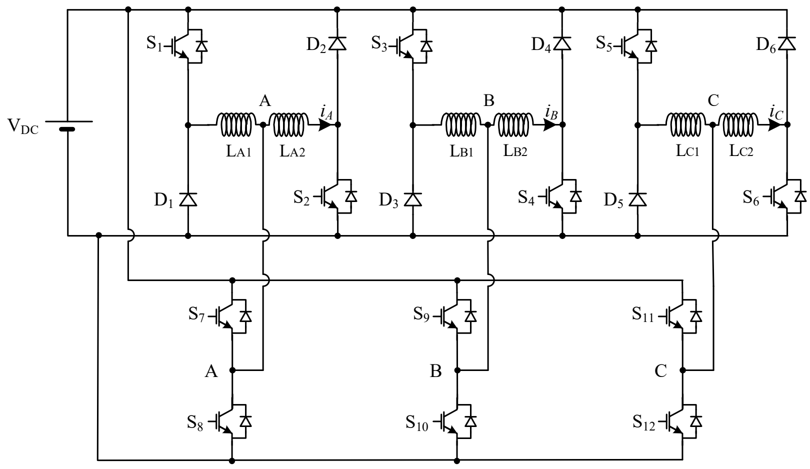


Figure 29. Fault-tolerant topology proposed by [94], combining a classic AHB topology and a classic redundant VSI topology applied to a three-phase SRM.

The fault-tolerant topology introduced by [95] uses an additional classic single-phase full-bridge (four controlled power semiconductors) combined with six mechanical relays for three-phase SRM. Figure 30 shows the proposed solution and possible combinations. Each converter phase is divided into three windings where additional controlled power semiconductors can be connected in a fault-tolerant operation. This solution can handle multiple open-circuit switch faults and open windings and is able to locate in which section of the winding is faulty. Multiple short-circuit failures are covered by the proposed topology similarly to the solution proposed in [94]. The two topologies work together to decrease, as much as possible, the influence of open-circuit or short-circuit failures in controlled power semiconductors or windings. Despite these features, the system performance at fault-tolerant is not similar to normal operation, even for single switch fault, since it always loses part of a winding. For multiple failures, the operation is even more degraded, since it uses the same additional leg to control more than one phase, which leads to the dependent control of phases rather than independent.

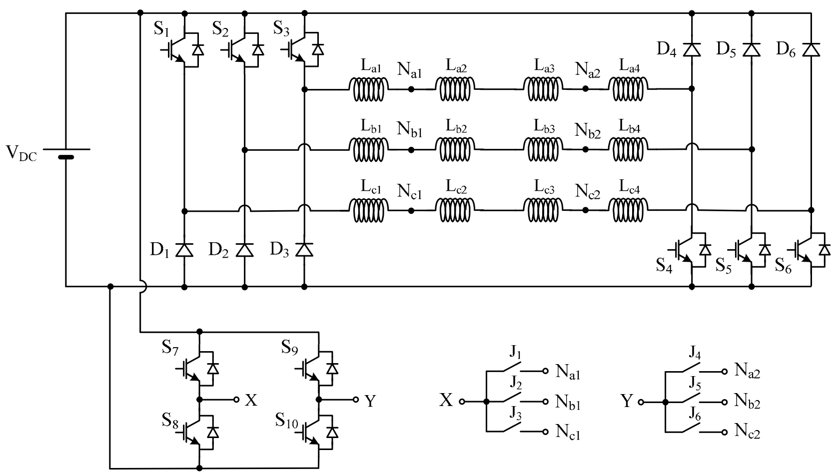


Figure 30. Fault-tolerant topology proposed by [95], which uses an additional classic single-phase full-bridge (four controlled power semiconductors) combined with six mechanical relays for three-phase SRM with split windings.

Another fault-tolerant topology was introduced by [96], based on using classic single-phase full-bridge (H-Bridge) converters for each phase coil. The proposed solution can be seen in Figure 31. The solution requires twelve converters for a six-phase 12/8 SRM, in which each phase winding consists of two coils, in order to be able to control each one independently. All the windings are split in two parallel connected coils (called channels). Two windings from opposite poles are connected to form a phase. In case of an open-circuit failure in a controlled power semiconductor, it is possible to invert the current excitation of all the coils without degradation of the system performance. In case of multiple open-circuit failures in the same converter, the system loses one coil. In this situation, the system performance is not the same as in normal condition. In case of short-circuit in a controlled power semiconductor, the authors propose the total isolation of the entire converter by opening permanently all the remaining switches of that bridge. In this situation, the system also loses one coil, similar to an open-circuit failure (although the demagnetization time is longer). The authors also present a comparison between 12/14 SRM and 12/8 SRM in order to compare the mean torques and percentage of the rated torque after losing a coil. The main disadvantage of this method is the high number of controlled power semiconductors and additional complexity to modify the machine structure.

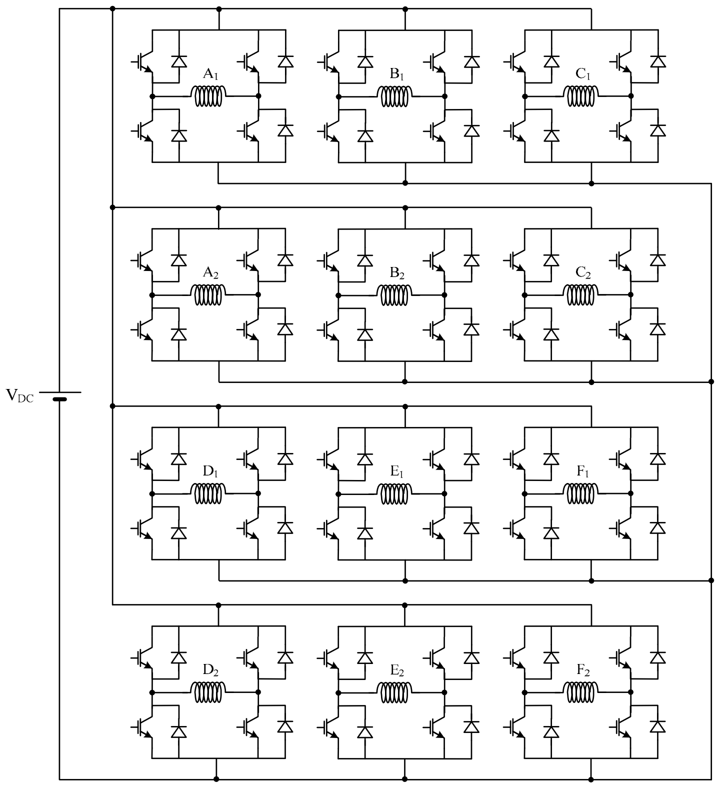


Figure 31. Fault-tolerant topology proposed by [96] based on using classic single-phase full-bridge (H-Bridge) converters for each phase coil. The solution requires 12 converters for a six-phase 12/8 SRM.

Another solution of this kind was proposed by [97] but applied to a four-phase SRM, each divided into two coils (or channels). However, this solution uses AHB converters for each phase coil, and it is not possible to invert the current excitation of all coils. Thus, the fault-tolerant capability to open-circuit failures is reduced when compared with [96], while the procedure, in case of short-circuit failures, is the same. The topology is not included in this review since is similar to Figure 30.

Based on the concept of increasing the number of inverter legs per phase, the authors in [98] use two inverter legs for each phase for a special six-phase 12/8 SRM to increase drive system reliability. The solution uses a mutually coupled dual three-phase SRM (DTPSRM). Figure 32 shows the proposed topology. Authors performed several experimental tests in different open-circuit (controlled power semiconductors or coils) faults and different operating conditions in order to demonstrate the fault-tolerant capability of this solution. The results indicate that the DTPSRM drive is able to maintain the command speed with one-, two- and three-phase open-circuit faults and can also successfully perform self-starting operation under lack of one- and two-phases with fault-tolerant control. Nevertheless, the system performance is not similar to normal operation even for single open-circuit fault. Short-circuit faults are not covered by the proposed topology.

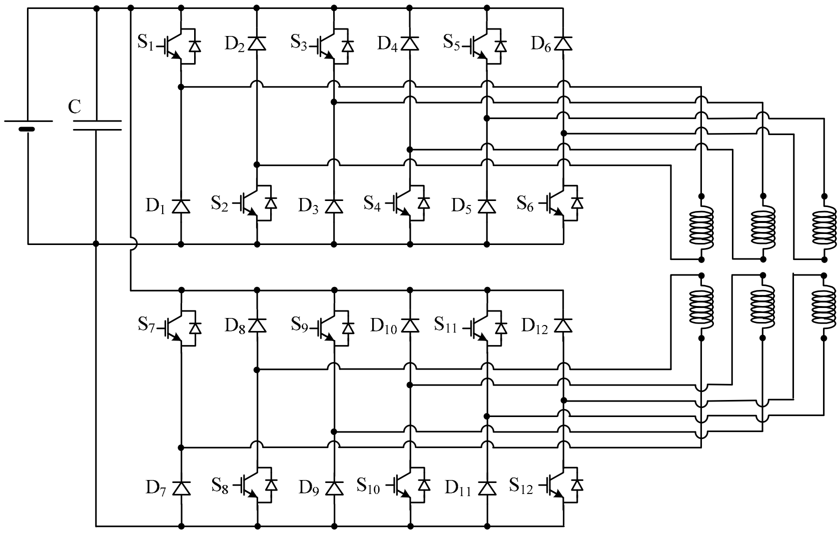


Figure 32. Fault-tolerant topology proposed by [98], based on the concept of increasing the number of inverter legs per phase. The solution uses a mutually coupled dual three-phase SRM (DTPSRM).

Another fault-tolerant solution based on a specific design of a DCSRM (dual-channel SRM), driven by two three-phase standard inverters, was introduced by [99]. The fault-tolerant strategy of this solution is focused on two main aspects. Firstly, in the SRM design and secondly, in the control strategy. These two aspects allow the SRM to have different behaviors, identified as Model I and Model II. The proposed DCSRM operates like one three-phase traditional SRM under Model I and works as two MCSRMs (mutually coupled SRMs) under Model II. Figure 33 shows the fault-tolerant solution proposed in this paper allowing the fault-tolerant operation. The terminal points (O_1 and O_2) are connected and the two channels (coils) of each phase have a specific arrangement. For example, under Model I, the switches S_1 and S_8 are controlled when the current is injected into A1 and A2 (phase A). After an open-circuit failure in S_1, it is possible to invert the current in phase A, controlling the switches S_7 and S_2, leading again to a normal operation. After a second open-circuit failure in phase A (e.g., S_7 or S_2), the currents of healthy phases will increase greatly, and the torque ripple will become unacceptable under Model I. In order to minimize the impact of this second failure, the machine will operate as Mode II. Under Model II, the current of O_1 and O_2 should keep close to zero to ensure no close loop current between channel 1 and channel 2 while a sine-wave current is injected. This is possible because the flux distribution of Model I is the same as that of conventional SRM (flux paths of channel 1 and channel 2 are in serial), while the flux distribution of Model II is the same as that of MCSRM (flux paths of channel 1 and channel 2 are in parallel). Then, the average torque remains by increasing the currents of healthy channel, and the torque ripple reduces through ripple current injection of healthy channel. Short-circuit faults are not covered by the proposed topology.

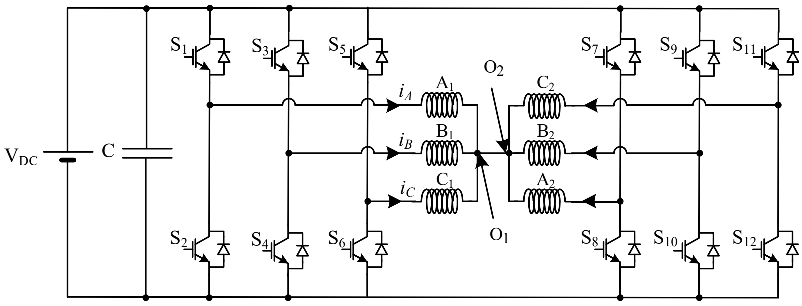


Figure 33. Fault-tolerant topology proposed by [99], on a specific design of a DCSRM (dual-channel SRM) driven by two three-phase standard inverters.

Another fault-tolerant topology based on multi-phase operation of SRM was introduced by [100]. This paper proposes a six-phase SRM drive with an additional fully controlled branch as show in Figure 34. In this topology, the SRM phases have a special arrangement and is possible to operate with one or two-phases to increase the output torque. The proposed topology combines the advantages of both AHB converter and split-phase converter, using two midpoint switches (S_7–S_8) in place of two large capacitors as happens with the midpoint-capacitor split-phase (NMCS) topology. For lower torque operation, each current phase is controlled separately using the main controlled power semiconductors (S_1–S_6) and the additional switches (S_7–S_8). For example, the current in phase A is controlled through S_1 and S_8 and the next phase (phase B) is controlled through S_2 and S_7. The control signals of S_7 and S_8 are complementary with fixed 50% duty-cycle. To ensure the effectivity of the modulation strategy, the switching frequency of midpoint switches must be 20 to 30 times higher than phase switches. All phase winding operates with Vdc/2. More than one phase winding can also be excited at the same time for higher torque and lower torque ripple in the proposed multi-phase SRM system. The fault-tolerant of the proposed solution is quite limited and the main improvement is only the capability to ensure independence of each phase after an open-circuit failure in phase switches which cannot be achieved with NMCS. Short-circuit faults are not covered by the proposed topology.

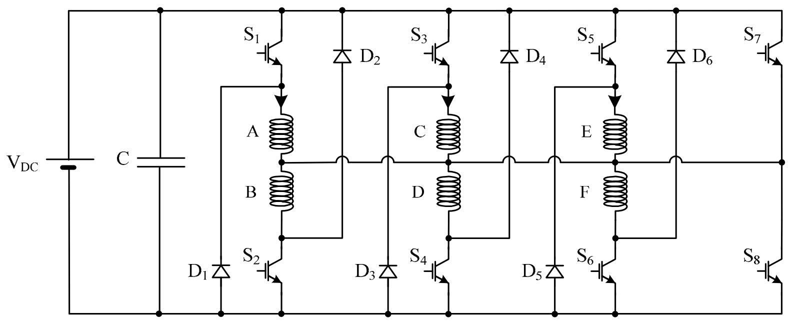


Figure 34. Fault-tolerant topology proposed by [100], combining multi-phase of SRM and two midpoint switches.

5.4. Comparative Summary of the Several Fault-Tolerant Topologies

A comparative summary of the fault-tolerant topologies can be seen in Table 4. In order to make this comparative study, several aspects were considered, namely the possibility to achieve full fault-tolerant operation, the failure modes covered by each topology, the possibility to operate under extreme faults, the additional controlled power semiconductors when compared to classic AHB, the number of static (or mechanical) switches, the possibility to extend the solution to other phase numbers, the control complexity and, finally, the need for special machine design. Regarding the control complexity, three different levels were considered to give a notion about the modifications and computing effort necessary to adopt the proposed solution, when compared to the classic AHB.

A low or reduced control complexity means that some modifications should be done in the control strategy and circuit, mainly to accommodate additional information about detection devices or gate drives, and new actions (connect or disconnect power devices or relays) must be undertaken based on such information. Typically, most solutions of this kind provide full fault-tolerant capability with no restrictions (or with slightly degraded operation) and are simpler and easier to implement, regarding the control strategy. On the other hand, the reduced control complexity is usually the most expensive since it is mostly based on replacing faulty devices (by redundant devices or legs) to continue the operation. A medium control complexity indicates that the proposed solutions require a significant amount of information from the detection devices and the decision algorithm must deal with all this information and select which and how the remaining devices should operate to provide fault-tolerance with minimum impact on the machine. This kind of solution is less expensive but requires additional modifications in the control strategy. The highest control complexity emerges, mostly, associated with solutions where the machine windings are modified (central-tapped or split windings) to provide fault-tolerance of power devices failures. In such solutions, the control strategy implies controlling the currents in the machine despite different windings paths and consequently different magnetization and demagnetization circuits. In some cases, the machine windings are ingeniously distributed on the periphery of the stator to obtain better performance in case of power semiconductors failure. This type of solutions usually leads to a complete and complex modification in the initial control strategy.

Table 4. Comparative summary of the fault-tolerant (FT) topologies.

Topology	Full FT Capability	Open-Circuit Faults	Short-Circuit Faults	Multiple Faults	Additional Controlled Power Semicond. Switches [(a)]	Number of Static Switches	Designed for any Number of Windings	Control Complexity	Machine with Special Design
Figure 22 [87]	Yes	Yes	No	Yes [(c)]	2	2/Phase	Yes	Low	No
Figure 23a [88]	Yes	Yes	Yes	Yes	2	2/Phase	Yes	Low	No
Figure 23b [88]	Yes	Yes	Yes	Yes	2	4/Phase	Yes	Low	No
Figure 24 [89]	Yes	Yes	No	Yes	4	4/Phase	Yes	Low	No
Figure 25 [90]	Yes	Yes	No	Yes	0	1/Phase	No	Low	No
Figure 26 [91]	Yes	Yes	Yes	Yes	2	4/Phase	Yes	Low	No
Figure 27 [92]	Yes	Yes	Yes	Yes [(b)]	6	4	Yes	Medium	No
Figure 28 [93]	Yes	Yes	Yes	Yes	6/Phase	0	Yes	Medium	No
Figure 29 [94]	Yes [(b)]	Yes	Yes	Yes [(c)]	2/Phase	0	Yes	High	Yes
Figure 30 [95]	Yes [(c)]	Yes	Yes	Yes [(d)]	4	2/Phase	Yes	Medium	Yes
Figure 31 [96]	Yes	Yes	No	Yes [(b)]	6/Phase	0	Yes	Medium	Yes
Figure 32 [98]	Yes [(b)]	Yes	No	Yes [(c)]	0	0	Yes	Low	Yes
Figure 33 [99]	Yes	Yes	No	Yes [(b)]	2/Phase	0	Yes	High	Yes
Figure 34 [100]	Yes [(c)]	Yes	No	Yes [(d)]	2	0	No	High	Yes

[(a)] when compared to the classic AHB; [(b)] Slightly degraded operation; [(c)] Moderately degraded operation; [(d)] Strongly degraded operation.

6. Conclusions

This work presents the state of the art on power electronic converter interfaces used in SRM drives to respond to the challenges imposed by different applications. This review shows that the interest in the SRM has grown over the last years and, consequently, the number of new and promising topologies and solutions also increased. This work is not limited to the two-level power converter topologies, but extended to new approaches. In line with this, the topologies were divided into four main groups, namely two-level, multilevel, impedance source and fault tolerant. Through this review, it is possible to understand how the choice of a specific topology influences the operation and performance of the SRM and the application itself. For example, for applications that require a wide speed range, the classical topologies based on two-level voltages are not generally the best option. New topologies and solutions based on multilevel voltages and/or impedance source networks that have been presented in the last years are usually more suitable for these applications. The growing interest in solutions using renewable energy sources has also led to the development of new applications combining, for example, photovoltaic systems and SRM drives. Such solutions usually require boost capability and this work also presents a review of topologies where such capability was incorporated. A significant part of this work was also dedicated to the review of SRM drives with fault-tolerant capability. Most of these fault-tolerant topologies were proposed recently and can be considered a new research area. Many works in this area are mainly dedicated to solving the problem of drive operation after an open-circuit failure in power switches, although a few of them are also dedicated to short circuit failure. Based on this review, it is also possible to conclude that three different approaches can be found, regarding the proposed fault-tolerant topologies. Finally, it should be noted that this review was only focused on the SRM. The other type of reluctance machine, the synchronous one, which is a true AC rotating field machine, requires a balanced polyphase sinusoidal supply into a distributed winding. This means that only power converter topologies that are used in AC drives should be used for this kind of machine, which can be considered for a future work in this area.

Author Contributions: Conceptualization, V.F.P. and A.J.P.; methodology, V.F.P. and A.C.; writing—original draft preparation, V.F.P. and D.F.; writing—review and editing, V.F.P. and A.J.P. and A.C. and D.F.; visualization, D.F.; supervision, V.F.P.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by national funds through the FCT-Fundação para a Ciência e a Tecnologia, under projects UID/CEC/50021/2019 and UID/EEA/00066/2019.

Conflicts of Interest: The authors declare no conflict of interest.

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