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REVIEW

Overview of grounding schemes for solid-state transformers in distribution networks

Jiajie Zang[1] | Jiacheng Wang[1] | Jianwen Zhang[2] | Jianqiao Zhou[2]

[1] School of Mechatronic Systems Engineering, Simon Fraser University, Surrey, Canada

[2] The Key Laboratory of Control of Power Transmission and Conversion of Ministry of Education, Department of Electrical Engineering, School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China

Correspondence
Jiajie Zang, School of Mechatronic Systems Engineering, Simon Fraser University, 250–13450 102 Avenue, Surrey, Canada.
Email: jza176@sfu.ca

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Abstract
Proposed to be the critical enabling component for future distribution networks, solid-state transformers (SSTs) have drawn much attention lately. They have a massive potential to help reduce size and weight, improve efficiency, integrate microgrids, renewables and energy storages in distribution systems, and can fulfil multiple grid functions such as bidirectional power flow control, fault isolation, system reconfiguration, and post-fault restoration. The introduction of these power electronics devices in distribution systems, however, also brings new challenges to the grid. Extra levels of electromagnetic interference, stray current, and personnel safety are among the most prominent practical issues that proper grounding arrangements can address. In this paper, considerations that should be factored into the grounding scheme design for SST ports with different voltage forms and levels are thoroughly reviewed and summarised. The characteristics of various grounding schemes used in AC and DC distribution systems are evaluated and compared in detail from different perspectives. Based on the comprehensive review, several combinations of grounding schemes are recommended for typical SSTs. In addition, the inclusion of new relay protection devices in the SST grounding scheme design, considering their characteristics and unique requirements, to enhance protection and reliability is also discussed.

1 | INTRODUCTION

Conventional line-frequency transformers (LFTs) are widely used in distribution systems at different voltage levels. In recent years, the concepts of active distribution network (ADN) and hybrid systems combining both AC and DC grid segments have been proposed along with the increasing adoption of renewable energy resources (RESs) and the development of power electronics technologies. Various power electronics-based devices [1], e.g. soft open points [2], hybrid transformers [3], and loop balance controller [4, 5], were proposed to act as critical nodes in future distribution systems to interlink grid segments with the same or different voltage levels. These new devices, herein generally classified as solid-state transformers (SSTs), share several standard functions, including,

- Serving as multiport nodes to interconnect distribution grids with the same or different voltage forms and levels [1];
- Serving as interfaces for distributed generation sites and energy storage systems [1, 2];
- Providing power flow and voltage control, electrical isolation, and power quality enhancements [1–19];
- Enabling fault detection, isolation, post-fault reconfiguration and restoration [1, 2, 4, 5]; and,
- Facilitating flexible power dispatch and optimisation when multiple SSTs work in coordination [1, 2, 4, 5].

However, concerns on the safety, reliability, and robustness of SSTs still hinder their acceptance in practical distribution systems [6, 7]. In contrast to the traditional grids enabled by LFTs, networks created with SSTs are subject to more complicated fault conditions and different types of interferences [8]. A thorough and reliable protection scheme is essential for a practical SST. A comprehensive protection scheme can be achieved using software control algorithms and hardware protection devices, including grounding arrangements, circuit breakers, fuses, disconnectors, and sectionalisers [9]. Grounding scheme plays a critical role in protecting SSTs under different scenarios [7, 10]. Under normal condition, common mode interference can be effectively suppressed by properly designed grounding schemes and the cooperation of control strategies. Under fault conditions, the overvoltage and overcurrent phenomena may be affected by the grounding schemes in different manners. For example, by increasing (or decreasing) the grounding impedance, severer overvoltage (or overcurrent) will appear and threaten the safety of the SST. Furthermore, suitable grounding schemes can limit the fault voltage and current and as such enable the fault-tolerant operation of SST. On the other hand, grounding scheme design also affects the selection of other protection devices in terms of sensitivity and selectivity.

Therefore, careful design of the grounding scheme of an SST is vital to its safety, reliability, and robustness enhancement. Major factors that should be considered in the grounding scheme design for a typical SST include,

- Structure and configuration of the connected grids;
- Grounding and protection schemes used in adjacent distribution systems;
- Voltage types and levels of the SST ports;
- Converter topologies of the SSTs;
- The mutual influence between different SST ports, including fault propagation and common-mode interference;
- Post-fault reconfiguration and restoration of the connected grids; and,
- Selection and coordination of the corresponding protection device.

The detailed design largely relies on the voltage levels of the grid, as well as the objectives of the grounding and protection. For medium-voltage (MV) distribution networks, ensuring stable system grounding and power quality is of primary concern, whereas for low-voltage (LV) distribution networks, personnel safety should be considered first.

Only a few grounding schemes have been discussed and explicitly evaluated for SST applications. In [7], resistance grounding and solid grounding are adopted in the MVAC and LVAC ports of the cascaded H-bridge SST. It proves that the MV side grounding can significantly affect the post-fault overcurrent and overvoltage by varying the grounding impedance; the LV-side grounding scheme's design should cooperate with the downstream protection devices to guarantee the safety of the SST. However, the SST DC port's protection is not discussed, where fault happened at this port would also affect the whole system. In [11], the evaluation of grounding design with different schemes for a multiport modular multilevel converter (MMC) SST was presented based on the short-circuit faults on both AC and DC ports. It indicates that more consideration should be taken in system reliability of the MV-side grounding while personnel safety is the most critical factor in the LV-side grounding.

The cooperation with the protection devices, however, was not discussed in this work. Most of the grounding designs for grid-scale power electronics apparatus are originated from the existing grounding schemes used in conventional distribution systems, e.g. resistance grounding and reactance grounding. However, considering their unique characteristics and different application scenarios from traditional equipment, no general guidelines of the grounding scheme design for SSTs exist in the literature. When more grid systems are interconnected with each other with these new devices, interferences generated under both normal and fault conditions could be propagated to the adjacent systems. Also, fault characteristics of SSTs with different topologies and grounding schemes are mostly unknown for the time being. For SSTs interfacing both AC and DC systems, the grounding schemes' mutual influence on both the AC and DC ports is not apparent. Moreover, the coordination between the grounding schemes and new protection devices is missing in the literature as well.

In this paper, based on a thorough review, the main issues affecting the grounding scheme design for SSTs with different topologies in future distribution systems are discussed and analysed. Major factors to be considered, such as the configuration and structure of the distribution systems, SST converter topologies, the impact of the grid interfacing isolation transformer, and coordination with relay protections, are described and evaluated in detail. The possible use of new relay protection devices in coordination with the SST grounding is also discussed. Suggestions of grounding schemes for typical SSTs used in different scenarios are provided based on the comprehensive analysis and evaluation. The focus of the paper is to provide a thorough overview of the grounding design for SSTs used in distribution systems with considerations of the relevant aspects from different perspectives. By including the related references and discussing the key points in a proposed framework, it intends to reveal the challenges and the possible future directions of this subject matter and serves as a comprehensive reference for researchers and practicing engineers in this field.

2 | THE NECESSITY OF GROUNDING SCHEME DESIGN FOR SSTS

The grounding scheme design for the SSTs is essential to the devices themselves and the connected distribution systems due to several reasons.

1. With the increasing integration of the RESs and the dc loads, more SSTs will be implemented in the distribution systems. The existing grounding schemes of the ac grids cannot solve the problems under normal or fault conditions caused by the grid interconnection achieved by the SSTs.
2. The mutual influence caused by the ac and dc system interconnection is not clear when different grounding schemes are adopted in the grid systems and the SSTs. Close-loop circuits will be created via the system grounding points and the SSTs with specific topologies under abnormal conditions leading to fault propagation.

In general, most SSTs can be classified into the six basic types in Figure 1, depending on their number of power conversion stages [12]. The single-stage SSTs in Figure 1(a,b) do not use high-frequency transformers and thus feature lower initial cost

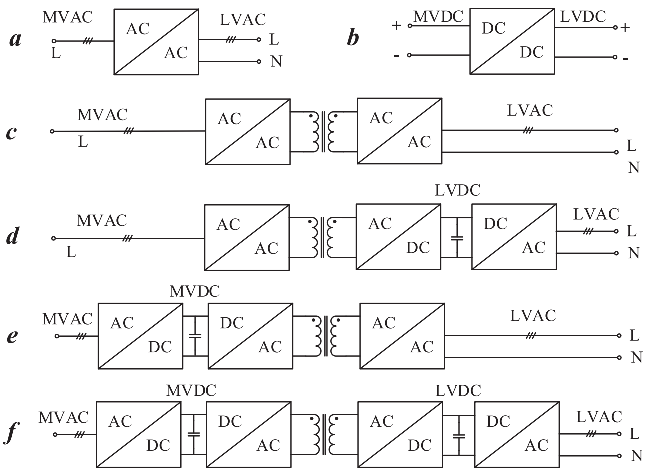

FIGURE 1 Typical SST structures. (a) single-stage type I, (b) single-stage type II, (c) two-stage, (d) three-stage type I, (e) three-stage type II, (f) four-stage

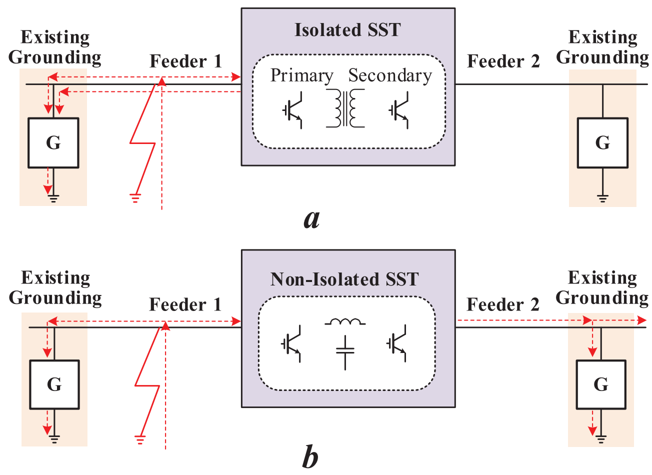

FIGURE 2 External fault circuit loops with (a) isolated SST; (b) non-isolated SST

and volume. Compared with the multi-stage SSTs, they only provide two converter ports with the same voltage type and can only fulfil a limited number of essential functions as listed in Section 1. Advanced functions such as fault isolation and system reconfiguration are not achievable with these converters. With the multi-stage SSTs as shown in Figure 1(c–f), galvanic isolation is provided via the built-in high-frequency transformers, and interference generated from either the MV- or LV-side can be effectively limited within a specific range. More converter ports are available in these structures for interconnecting different types of grids, where power can be flexibly transferred from/to the ports via the SST. The system can be reconfigured to isolate the faulty feeders and maintain the power supply in the healthy connected systems with less quality degradation. However, more power conversion stages lead to higher conduction losses, and the use of more power electronic devices decreases the reliability of the SST. Depending on whether isolation transformers are employed in their topologies, these grid-scale SSTs can also be classified into the isolated types [7, 13, 14] and the non-isolated types [15–18]. As shown in Figure 2, different fault current paths can be found in these two groups. As discussed in [7], the fault conditions can be classified into internal and external faults. The internal faults are not as severe as the external cases regarding the overcurrent and overvoltage levels and will not be discussed in detail.

One of the most common external fault conditions, single line-to-ground short-circuit (SLG) fault, happening between the existing remote grounding and the SST is depicted in Figure 2. Assuming there are no local protection devices installed for the SST, the fault circuit is formed between the fault point and the remote grounding point in the connected grid. For an isolated SST, faults happening at one port can be effectively confined within the SST converter's faulty side and the feeder, as shown in Figure 2(a), where the dashed lines with arrows indicate the fault current paths and directions. The most common example of isolated type SST is depicted in Figure 3 [19]. The AC fault current loop, in this case, is created between the fault point and the grounding points of the grid (AC and DC sides), as given in the red lines of Figure 3; the DC fault current will flow the same paths as that of the AC fault and will not be discussed further.

Furthermore, if a non-isolated SST is used, such as a back-to-back converter as given in Figure 4, the fault current will flow through the SST and common DC bus to the healthy ports with certain switching states under an SLG condition. The same conclusion can be reached in the DC fault conditions. Therefore, regardless of which type of SST is installed, the fault circuits will always be created involving part of the SST. The resultant phenomenon of overcurrent or overvoltage would pose significant challenges to the power electronic devices' ratings. The amplitudes of the overcurrent and overvoltage under fault conditions can be efficiently suppressed by a feasible grounding scheme design.

3. In general, the rated load current is between 40% to 50% of the maximum ratings of the selected power electronic devices used in the SST. To deal with the abnormal conditions, SSTs can use different reactions, such as enabling fault-tolerant operation and completely shutting down the SST. Fault-tolerant operation requires the coordination of the grounding scheme design and the fault ride-through control scheme to suppress the fault voltage and current within the rated values. If the voltage or current exceeds the protection threshold, the SST needs to be shut down to ensure device safety.

4. The SSTs are more vulnerable than traditional devices. It should be noted that the traditional LFT can sustain 20 kV dielectric for 1 min during short circuit condition and the oil insulated LFT has the overload capabilities of 25× the rated current for 2 s, 11× for 10 s and 3× for 300 s [7]. In contrast to the LFT, the SSTs can bear the maximum overcurrent of 1.5× for several minutes and 4× for some milliseconds [6, 7, 20]. Besides, power electronic semiconductors cannot withstand voltages higher than their maximum blocking voltage capability and usually keep 40% to 70% voltage margin to deal with the short-circuit fault conditions for several hundred milliseconds [20, 21].

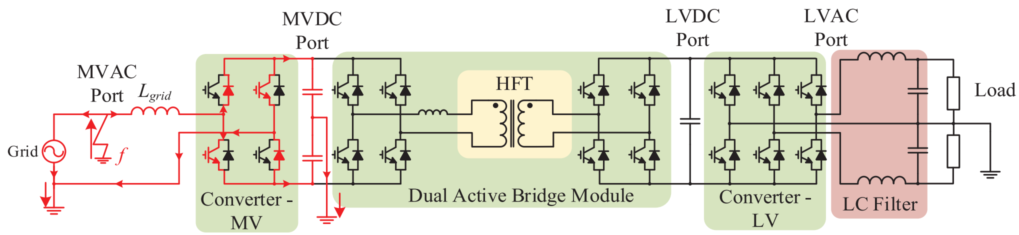

FIGURE 3 SLG fault current path in multi-stage SST

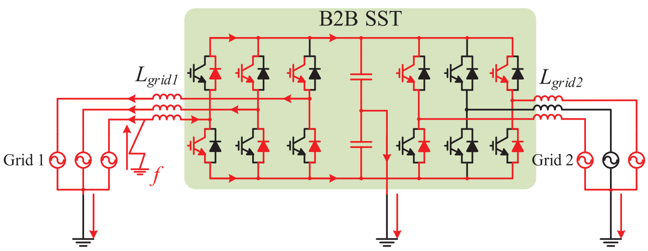

FIGURE 4 SLG fault current path B2B Type SST

Because of the interference propagation issue [22] and the vulnerability of semiconductor devices, a comprehensive protection scheme is indispensable to guarantee the safety, reliability, and robustness of the SST systems and the connected distribution networks. Figure 5 gives an overview schematic of the protection scheme based on traditional protection devices, including grounding methods, circuit breakers, fuses, surge arrestors, and disconnectors [7]. (1) The disconnectors are used to isolate the SST under the small current condition for device maintenance; (2) Fuses and breakers are applied to segregate the overcurrent with different time selectivity. (3) Surge arrestors are implemented at each port to clamp large overvoltage; (4) Nevertheless, the grounding scheme not only coordinates with the protection devices to isolate the fault conditions, but it provides a stable reference for the normal operation of the SST as well. Therefore, the grounding scheme plays an important role in the protection scheme of the SST and influences the selection of the protection devices in terms of the sensitivity, selectivity, and speed.

For SSTs with a higher number of ports, the fault characteristics analysis will be more complicated, requiring a feasible grounding scheme design for the grid-tied SSTs. Consequently, the grounding scheme design draws great concern in protecting the SST to enhance the system's safety, reliability, and robustness.

3 | GROUNDING SCHEMES FOR SSTS IN FUTURE DISTRIBUTION SYSTEMS

A grounding scheme usually has three essential purposes, namely, safety grounding, functional grounding (or signal grounding), and electromagnetic interference (EMI) control grounding [23]. While safety grounding is related to the protection of the system and personnel from electric shock, risk of fire hazard, and appliance damage; and functional grounding is used to offer a stable reference potential for circuits and systems; EMI control grounding, on the other hand, is designed to satisfy the electromagnetic compatibility requirement of the systems. The selection criteria of grounding schemes for SSTs vary depending on the connected distribution systems' voltage levels. In an MV network, functional grounding and EMI control grounding are primary concerns, as service continuity and power quality need to be guaranteed to the maximum extent. By contrast, LV distribution systems are more accessible to end-users, and therefore personnel safety should be considered in

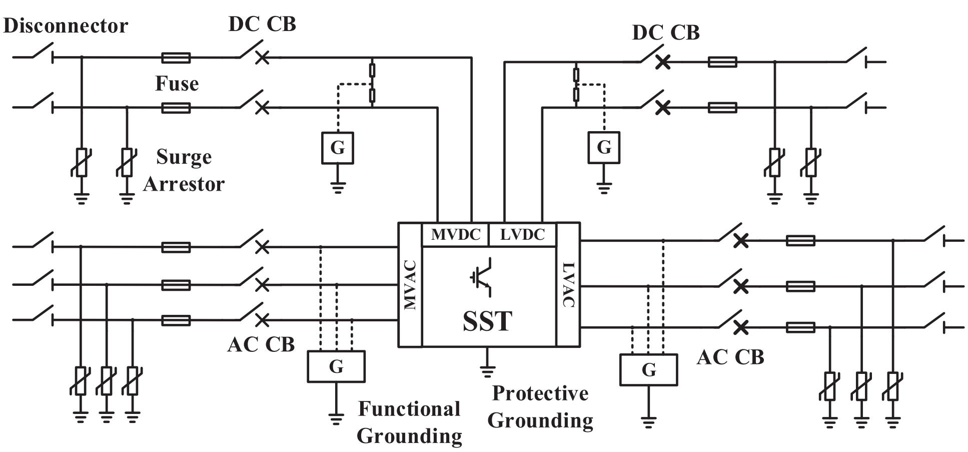

FIGURE 5 Schematic of the protection scheme of the SST

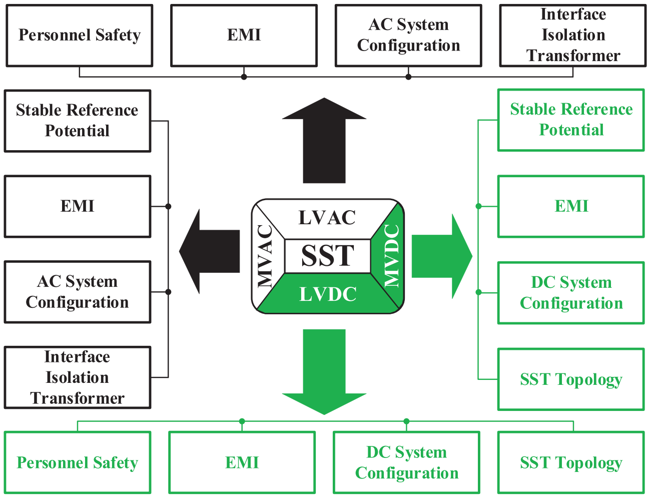

FIGURE 6 Factors to be considered in the grounding design for SSTs

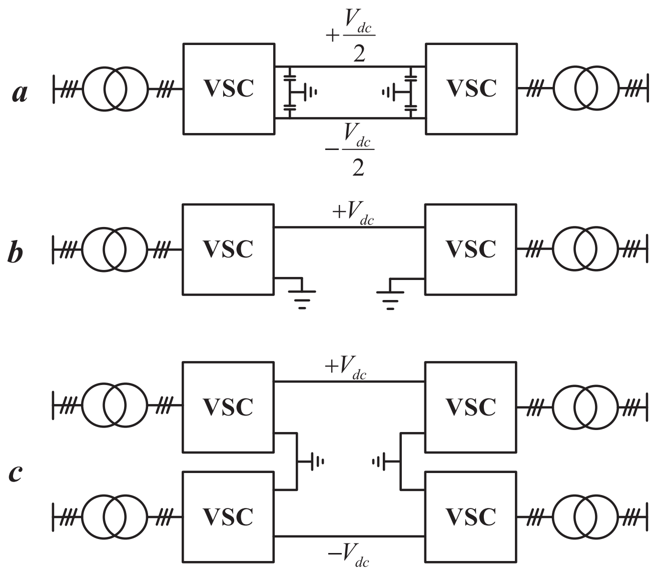

FIGURE 7 DC distribution system configurations. (a) symmetrical monopolar; (b) asymmetrical monopolar; (c) symmetrical bipolar

the first place. At the LV level, the EMI control grounding also needs to be considered to mitigate power losses and EMI pollutions. Two fundamental rules should, in general, be followed in the grounding scheme design of SSTs: (1) the design should comply with local grid codes and ensure maximum consistency of the system grounding and protection practice; (2) the design should also take into consideration the characteristics of the SSTs and satisfy their requirements.

Starting with a general overview of grounding schemes for both MV and LV distribution systems, this section will clarify the primary considerations in the design of grounding for a distribution-level SST. Detailed discussions and recommended designs will follow according to the same categorisation based on voltage levels and types.

3.1 | General considerations of grounding design for an SST

Several major factors should be considered in the detailed grounding scheme design for distribution-level SSTs, including (1) the types and configurations of the connected distribution systems; (2) the existence of isolation transformers at the SST ports; (3) the topologies of the SSTs. Most SSTs proposed so far can be generally categorised into the AC/DC, AC/AC, and DC/DC types. As a generic representation, Figure 6. illustrates a simplified SST with multiple ports of different voltage forms and levels, i.e. MVAC, MVDC, LVAC, and LVDC. Factors that need to be considered in the grounding design for each port are also given in the figure. The grounding schemes can be implemented in conjunction with circuit breakers (CBs).

As shown in Figure 6, grounding design at all the SST ports should first consider the local distribution system configuration. The AC ports are usually connected with three-phase three-wire or three-phase four-wire distribution networks, where the systems should be grounded to the earth or neutral line, respectively. For systems tied to the DC ports, as shown in Figure 7, typical arrangements include the asymmetrical monopolar, symmetrical monopolar, and symmetrical bipolar configurations [24, 25]. Each of these has its specific grounding design and implementations. Due to the possible combinations, the design and location choice of the grounding schemes around an SST is mostly dependent on the type and configuration of the distribution networks the SST is interfaced with.

For example, for an SST interconnecting an AC grid and a DC grid with the same voltage level, two possible sites, one at the AC port and the other at the DC port, can be found for implementing the grounding. Assuming the AC side is ungrounded, if the symmetrical monopolar configuration is adopted on the DC side [26, 27], as shown in Figure 7(a), the grounding scheme at the DC port can be implemented at the DC mid-point to create a stable reference potential; However, if the SST is connected to a DC network with asymmetrical monopolar configuration [28–30], as can be seen in Figure 7(b), one of the DC buses should be grounded to serve as the return path; If the DC side is of the symmetrical bipolar configuration [24, 31–36], as shown in Figure 7(c), the grounding should be arranged at the natural DC neutral point to provide a stable reference potential. Therefore, the bus voltages and currents of the positive and negative poles can be maintained separately, and the whole DC structure can be regarded as the combination of two asymmetrical monopolar systems.

The SST grounding scheme selection also depends on whether line-frequency interface isolation transformers are present at their AC ports. If an interface isolation transformer exists, it provides a convenient location for implementing grounding and helps mitigate mutual influences such as EMI and fault propagation from both the grid- and the converter-side. Different AC-side fault characteristics with or without interface isolation transformers were investigated for a modular multilevel converter (MMC) based HVDC system [37]. It was revealed that the transformer could be readily used to implement the grounding for the MMC and effectively contain

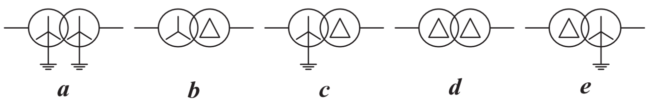

FIGURE 8 Interface isolation transformers. (a) Yg/Yg; (b) Y/Δ; (c) Yg/Δ; (d) Δ/Δ; (e) Δ/Yg

potential fault propagation. Characteristics of faults happening at different locations on the DC side of an SST under different grounding designs are analysed and compared in [38] for an MVDC distribution system, based on which several suitable schemes for the SST were provided. It indicated that transformers with Δ/Yn configuration are preferred due to their low common-mode voltage under SLG faults and their fault restoration capability under SPG faults.

Additionally, the transformer's winding configuration also affects the location choice of the grounding scheme. As shown in Figure 8, an isolation transformer can have several different winding configurations such as Yg/Yg, Y/Δ, Yg/Δ, Δ/Δ, and Δ/Yg in both MV [24] and LV distribution networks [39]. All the wye-connected configurations can provide a neutral point to implement the grounding directly. However, for delta-connected windings, extra grounding transformers (zig-zag transformers or Y/Δ transformers) or star-connected reactance are required to provide an artificial neutral point. A zig-zag transformer has several advantages: low installation area, low loss, and low reactive power consumption, as indicated in [40].

Thanks to the development of converter topologies and control strategies, many transformer-less SSTs have been proposed lately to further reduce the initial cost and volume [41–46]. Since there is no interface transformer to provide isolation and place the grounding, these SSTs are more vulnerable to various fault conditions. In these cases, extra devices such as differential- and/or common-mode filters are often employed to reduce the interference from both grids- and converter-side of the SST. During normal operation, the EMI generated by the SSTs can be limited by the filters to an acceptable degree to comply with the local grid code. Under fault conditions, an extra fault current loop can be constructed between the filters' grounding points and the fault point. The amount of fault current flowing through the filters' grounding points may exceed the devices' rating limits in this loop if there is not a suitable grounding scheme in place. So far, fewer studies can be found on the grounding scheme design of transformer-less SSTs. In [21], the grounding concept accompanied by a common-mode filter design for a transformer-less MV drive was presented, where the common-mode interference can be limited within the drive system under normal conditions. However, grid-side fault conditions were not covered in the work. In the transformer-less concept, additional high-amplitude common-mode voltage sources would be introduced to the system under fault conditions. Excessive faulty current cannot be entirely suppressed by the filters and will be further transferred to the other grounding points, and even destroy the connected devices if the impedance of the fault current loop is low. To that end, grounding schemes

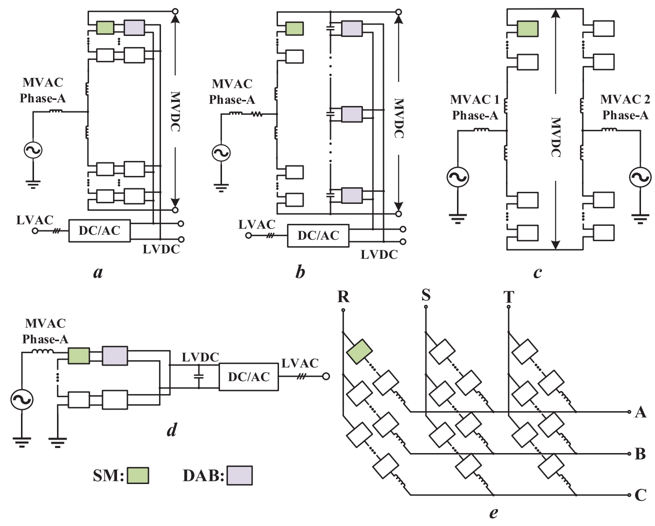

FIGURE 9 Examples of the SST topologies. (a) MMC-SST type I; (b) MMC-SST type II; (c) B2B MMC; (d) CHB-SST; (e) AC/AC direct MMC

are indispensable in transformer-less cases and should be even more carefully considered for normal and fault conditions.

Finally, the topologies of the SSTs also influence their grounding scheme design from different perspectives, especially at the DC ports. Various SST variants have been adopted to interface distribution systems with different MV systems' voltage levels. The proposed topologies include MMC [41], two-level full-bridge converter [42], neutral point clamped converter [47], and cascaded H-bridge converter [48]. Figure 9 illustrates several modular SSTs constructed by multiple submodules (SM) and/or dual active bridge modules (DABs). These modular SSTs can be regarded as the expansion of the SST given in Figures 3 and 4. Modular multilevel structures are preferred in the MV distribution level to solve the semiconductors' limited voltage issue and obtain better output performance. Figure 9(a,b) illustrate the single-phase diagram of two types of modular multilevel converter (MMC) based SST that four ports can be attained to interconnect different distribution systems. Figure 9(d) shows the single-phase cascaded H-Bridge converter (CHB) based SST, which provides three ports, such as MVAC, LVDC, and LVAC ports. In Figure 9(a,b,d), dual active bridge modules are adopted to transfer the power between the MV and LV level and realise the galvanic isolation. A back-to-back MMC based soft open point and a direct AC/AC MMC are depicted in Figure 9(c,e). No transformers are used in these two subfigures, and as such, the connected feeders are not galvanic isolated.

It should be noted that only full-bridge SM can be used in Figure 9(e). CHB-SST owns a natural neutral point that can be used to implement the grounding schemes. However, in MMC-SST, the DC capacitors are evenly distributed in the submodules where no original neutral point can be provided at the MVDC port. Hence, auxiliary devices, e.g. split resistors, are required to form an artificial neutral point. For the other topologies, such as the ones shown in Figures 3 and 4, grounding schemes can

TABLE 1 Potential grounding schemes implementation points for the existing SST prototypes

Types	Prototypes	Power	Potential grounding schemes implementation points			
			MVAC	MVDC	LVAC	LVDC
CHB based	ABB [111, 112] 1 ph	1.2 MVA	Neutral point	NA	Neutral point	Mid-point
	FREEDM 1 ph [113]	20 kVA	Neutral point	NA	Neutral point	Mid-point
	HUST 3 ph [114]	500 kVA	Neutral point	NA	Neutral point	Mid-point
	UNIFLEX [115] 3 ph	300 kVA	Neutral point	NA	Neutral point	Mid-point
MMC based	IEECAS I [116]	1 MVA	Neutral point	Mid-point	Neutral point	Mid-point
NPC based	EPRI [117] 1 ph	100 kVA	Neutral point	NA	Neutral Point	Mid-point
	FREEDM 1 ph [113]	20 kVA	Neutral point	NA	Neutral point	Mid-point

be implemented at the DC ports' neutral points provided by the split DC capacitors.

So far, only a few grounding schemes are investigated in simulations to deal with certain abnormal conditions of SSTs. These schemes are yet to be tested in practical systems. For existing SST prototypes, seven implementations are listed in Table 1 and categorised based on their topologies, including the neutral point-clamped (NPC) type, the CHB type, and the MMC type. While the specific grounding arrangements of these prototypes were not discussed in detail in the above-listed references, the potential points of grounding implementation of the NPC based SSTs are similar to those of the CHB based systems. In the CHB based SSTs, the MV-side grounding can be implemented at the natural neutral point of the MVAC port. The LV grounding schemes can be arranged at the neutral point of the LVAC port and the midpoint of the LVDC port. By contrast, the MMC type SSTs do not have a natural neutral point at the MVAC port, and therefore require devices such as isolation transformers or grounding transformers to create artificial neutral points for implementing the grounding. The DC-side grounding schemes can be realised at the mid-points of the MVDC and LVDC ports. The LVAC grounding scheme can also be realised via the grounding transformers and/or three-phase-four-leg converters. The specific grounding schemes of the prototypes may vary due to the different regulations set by the local grid operators.

It should be noted that the detailed grounding arrangements are related to the requirements on system fault isolation and protection. Since the SSTs are the interface devices between the AC and DC distribution systems, fault incidents should be confined to not to harm the SSTs and the connected feeders. All the factors mentioned earlier should be considered to design an optimal grounding scheme for any SST. Moreover, trade-offs may have to be made to meet a specific system's grounding requirements.

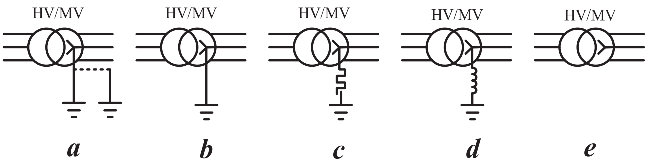

FIGURE 10 MVAC grounding schemes. (a) neutral distributed with multiple grounding points; (b) neutral grounded directly and undistributed; (c) neutral grounded via an impedance; (d) neutral grounded via a designated circuit; (e) ungrounded

3.2 | Grounding schemes for SSTs at the MV level

In general, the grounding schemes at the MV level share similar design criteria with the high-voltage (HV) systems, focusing mainly on functional and EMI control grounding. In MV and HV grids, solid grounding, resistance grounding, reactance grounding, resonant grounding, and ungrounded systems are typically adopted to meet different grid codes [49, 50].

3.2.1 | Grounding schemes at the MVAC port

On the MVAC side of an SST, grounding schemes implemented in current MVAC distribution systems can be readily adopted. As shown in Figure 10, MVAC grounding schemes mainly include the following types, i.e. neutral distributed with multiple grounding points, neutral grounded directly and undistributed, neutral grounded via an impedance [51], neutral grounded via a designated circuit such as a Peterson coil, and neutral ungrounded [50, 52]. Moreover, the hybrid grounding scheme was proposed to achieve a better protection performance in the MV generators by adjusting the value of the grounding resistance from low to high [53]. Though the hybrid grounding scheme has been proposed where grounding resistance can be shifted under different conditions, the adopted switch's response speed is still unknown for the SSTs used in the ADN. These grounding schemes can be categorised into the large fault current group and the small fault current group based on the amplitude of the zero-sequence fault current and the arc self-extinguishing capability [49, 54].

The SLG fault is usually accompanied by overvoltage and overcurrent issues which influence the insulation level, safety of the connected apparatus, and power service continuity of the affected grid. To verify the effectiveness of any possible grounding scheme on the MVAC side of an SST, the ratio between the SLG short-circuit fault current and the three-phase fault current, $I_{SLG}/I_{3\Phi}$, is used as an evaluation metric. The large fault current group includes the solid grounding and small impedance (resistance, reactance) grounding schemes. The ungrounded, high impedance (resistance, reactance) grounding and resonant grounding schemes belong to the small fault current group. These grounding schemes are usually separately used based on the SLG fault current amplitude in practical applications. At the MV level of 10–66 kV, if I_{SLG} is under 10 A, ungrounded systems are recommended for the distribution network. When the fault current falls in the range of 10 A to 100 or 150 A, it is preferred to use resonant grounding to limit the fault current to be within 10 A. If the fault current is larger than 100 or 150 A, low-resistance grounding is usually the preferred choice, where circuit breakers or fuses will be easily tripped by the large fault current to isolate the fault in such systems.

These grounding schemes are associated with different characteristics in terms of requirement of the basic insulation level (BIL), transient overvoltage (TOV) level under SLG fault, service continuity under SLG fault, personnel safety, thermal stress, EMI level, and relay protection sensitivity and coordination [49, 55–57].

As shown in Figure 10(a,b), the two solid grounding schemes with different configurations are usually adopted in the current North American MVAC distribution systems. Under these schemes, the TOV associated with the SLG fault condition can be properly controlled. However, a large fault current will be generated due to the fault circuit's small impedance, leading to potential fire hazards and arc-flash. The ground potential would be raised from 0 to $I_f Z_f$ and may result in step-voltage issue [58], where I_f and Z_f are the fault current and the equivalent resistance of the fault point, respectively.

As shown in Figure 10(c,d), the grounding schemes via a neutral impedance include several possible subtypes, i.e. low-resistance grounding, low-reactance grounding, high-resistance grounding, high-reactance grounding, and resonant grounding [49, 56, 58]. Although the ratio of $I_{SLG}/I_{3\Phi}$ can be limited to between 5% to 25%, the high reactance grounding is not preferred because its excessive TOVs during an SLG fault would necessitate extra protection devices to be added. Low-resistance grounding is popular in MV systems ranging from 2.4–34.5 kV with the capacitive short circuit fault current larger than 150 A. Distribution systems with low-resistance grounding needs to be shut down to prevent high magnitude fault currents once the fault is identified [49, 58–60]. High-resistance grounding is often used in systems in the range of 480–4,160 V, where the fault current can be suppressed to 0.5–10 A, thereby minimising fire hazard and personnel safety issues. In such cases, the TOV can be reduced to less than 2.73 p.u. of the nominal line voltage. However, the sensitivity and selectivity of relay protections are restricted because of the small fault current magnitude. As power is allowed to be transferred continuously during the fault, these systems are required to have a high insulation level, which increases the initial cost [55, 58, 60–62]. Low-reactance grounding is often used for managing high ground-fault currents in substations and generators with single-phase loads where voltage levels are below 600 V or above 15 kV. It is largely replaced by the more modern resonant grounding schemes in today's distribution systems worldwide and is rarely used anymore [58, 60]. Resonant grounding schemes are popularly adopted in countries and regions such as Italy, Northern and Eastern Europe, Israel, and China. Its capacitive fault current can be compensated to essentially zero, and the TOV caused by the SLG fault can be limited to below 2.73 p.u. This method is usually designed to work in overcompensation mode to cope with the abnormal conditions and the increasing use of cables. The trade-off between the overvoltage and overcurrent issues caused by different grounding impedance is discussed and verified in [38], where it was shown that the fault performance could be optimised by adjusting the grounding impedance.

Ungrounded systems have been adopted in Germany, Italy, UK, Japan, Ireland, and China, with the advantages of the least initial investment and service continuity under the SLG fault condition [50, 63]. As shown in Figure 10(e), since the neutral point is floating in such systems, the fault current can only circulate from the fault point via the power lines' distributed capacitors back to the ground. The magnitude of the fault current is low, and $I_{SLG}/I_{3\Phi}$ is typically less than 1%. The phase voltages of the healthy feeders increase to the line voltage level during the fault, and the TOV can be even larger than three p.u. [49]. To maintain the power supply, the relay protections' sensitivity should be low to avoid spurious tripping. Also, although the line voltages remain unchanged under the SLG fault, appliances can only be connected between the live lines to prevent damages caused by the rapid change of phase voltages.

Detailed comparisons of the above-described grounding schemes for the MVAC port are given in Table A1. Here, X_0 and R_0 represent system zero-sequence reactance and resistance, respectively; and X_1 is the positive-sequence reactance. For the large current grounding schemes, due to the small impedance of the fault loop, the grounding location is determined by the local grid system configuration and the existence of isolation transformer. The grounding scheme design should also consider the SST specifications such that the safety of the circuit elements can be guaranteed. Moreover, the detailed design should follow the local grid codes to ensure proper coordination with the existing grounding implemented and the corresponding relay protections of the MVAC distribution system to avoid conflicts and spurious tripping.

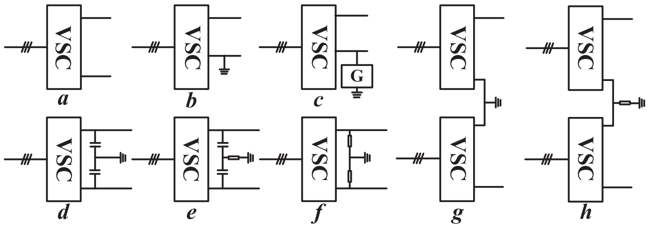

FIGURE 11 MVDC grounding schemes. (a) ungrounded; (b) solidly grounded asymmetrical monopolar; (c) diode or thyristor grounded asymmetrical monopolar; (d) capacitance mid-point solidly grounded symmetrical monopolar; (e) capacitance mid-point grounded symmetrical monopolar with neutral resistor; (f) clamped resistance grounded symmetrical monopolar; (g) solidly grounded symmetrical bipolar; (h) grounded symmetrical bipolar with neutral resistor

3.2.2 | Grounding schemes at the MVDC port

Figure 11 illustrates the typical grounding schemes used in the current MV and HV DC applications. These include: ungrounded [40, 64], solidly grounded asymmetrical monopolar [30], capacitance mid-point solidly grounded symmetrical monopolar [64], capacitance mid-point grounded symmetrical monopolar with neutral resistor [65], clamped resistance grounded symmetrical monopolar [65, 66], solidly grounded symmetrical bipolar [32], and grounded symmetrical bipolar with neutral resistor [31].

As shown in Figure 11(b,c), the grounding schemes are usually adopted in DC systems with asymmetrical configurations, e.g. DC rail systems. Although the ungrounded solution in Figure 11(a) generates the least stray current, personnel and equipment safety are threatened by the increase of the voltage potential under fault conditions [67]. It is also difficult to identify abnormal conditions because of the lack of proper fault current measurement locations. A diode or a thyristor can be added to the negative bus of the ungrounded DC system to provide a site for the installation of fault detection and isolation devices, as shown in Figure 11(c) [30, 66]. It should be noted that the added diode or the thyristor also introduces a higher level of stray currents, which increases the risks of corrosion of the metallic conductors around the grounding point. The method illustrated in Figure 11(b) is not preferred in modern systems because the DC system's negative bus is directly grounded, which increases the threat of corrosion to underground facilities close to the rail tracks [30].

The grounding arrangements illustrated in Figure 11(d–f) are usually used in symmetrical monopolar systems, and which one to choose in a specific design should be determined by the topology of the SST. For instance, if the SST is based on the MMC topology, as the DC capacitors are floating and distributed in the MMC submodules, no neutral point on the DC port can be provided [28]. Thus, extra resistances are needed to form an artificial neutral point, as shown in Figure 11(f). However, if the SST is built with topologies that offer a natural neutral point on the DC side, all the schemes in Figure 11(d–f) can be readily applied. For the capacitance mid-point solidly grounded symmetrical monopolar configuration shown in Figure 11(d), large discharging fault current and high TOV will be generated under an SPG fault, the level of which may exceed the rated voltage of the power electronics devices and result in undesirable damage. Due to the large current amplitude, the fault can be easily detected and cleared by the relay protections. In Figure 11(e), a neutral grounding resistor is added to limit the magnitude of the fault current, where the value of the resistor should be carefully designed to maintain the voltage balance between the two poles. Extra control schemes may be required to further reduce the common-mode voltage between the poles such that the power loss can be curtailed [65, 66]. As described above, the configuration of Figure 11(f) consists of two additional resistors to form the artificial neutral point and is often used with MMC based SSTs [28, 66, 68, 69]. The last two grounding schemes, as given in Figure 11(g,h), are always applied in symmetrical bipolar systems [24, 31–35, 65, 66]. These methods share the same features with the symmetrical monopolar types in Figure 11(d–f).

The above-mentioned grounding schemes' assessment should take different perspectives such as the magnitude of the zero-sequence fault current, TOV, BIL, EMI, the difficulty of the fault diagnosis, power loss, and the fault-tolerant operation of the SST. The EMI level, stray current, and power loss, among others, are the main criteria for the evaluation of the grounding schemes under normal operation. The other criteria are used to test the grounding schemes' performance under fault conditions. All the small fault current grounding schemes share almost the same features, such as high TOV and low fault current due to the high impedance in the fault current loop. The fault detection and system protection are set with lower sensitivity to achieve fault-tolerant operation. However, the fault-tolerant operation is associated with several hidden issues, such as the high possibility of secondary faults occurrence and the challenge to the connected distribution feeders' insulation level, threatening system and personnel safety. The large current grounding schemes are associated with opposite characteristics to the small current grounding schemes. They are generally characterised by high fault current, low TOV, and low BIL. Given the high fault current amplitude, high-speed fault identification can be easily realised to improve both the system and personnel's safety. But the system cannot continue operation under faults because the DC voltage cannot be maintained. The choice between adopting the large fault current grounding schemes with potential overcurrent and using the small fault current grounding schemes with possible overvoltage depends on specific design objectives. These issues would challenge the voltage and current ratings of the power electronic devices in the SST and the connected feeders.

A comparison of feasible grounding schemes at the MVDC port is given in Table A2. In deciding the grounding location and type at the MVDC port of an SST, both the SST's topology and the DC distribution system's configuration should be considered. Like the MVAC side, a detailed grounding scheme design for the MVDC port relies on the existing grounding and relay protections implemented in the connected DC distribution system.

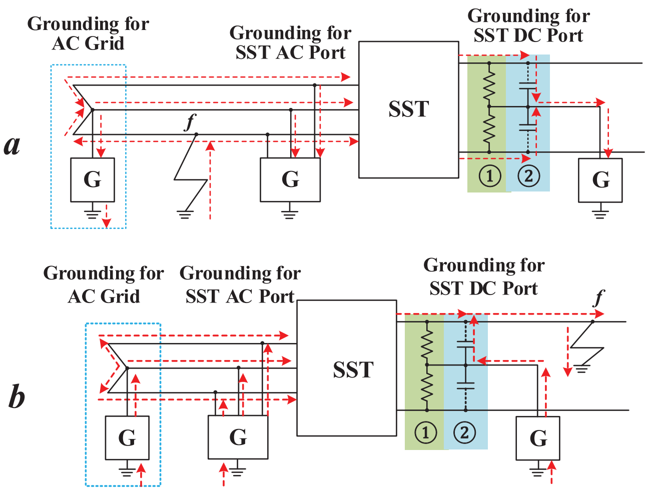

FIGURE 12 Fault current paths with grounding schemes arranged at both the AC and DC ports. (a) SLG fault condition; (b) SPG fault condition

3.2.3 | Recommendation of grounding combinations for the SST MV ports

Due to the nature of the multiport SSTs, a holistic design approach combining MVAC and MVDC configurations and grounding schemes should be adopted to improve the system function and performance. The grounding designs should follow the local grid codes and maintain consistency in terms of grounding fault current magnitude. Otherwise, potential spurious triggering of the fault protection schemes could happen and affect system operation because of different grounding groups' inconsistent sensitivity levels.

On the MVAC side, there are two possible grounding scenarios: (1) the SST shares the same grounding scheme with the grid, and (2) the SST has its AC grounding scheme. In the first case, investment in the extra grounding scheme arranged on the SST AC port can be saved at the cost of the possible fault propagation on the AC distribution system. The second scenario is more suitable and preferred as it avoids fault propagation and provides better protection for the system and SST under abnormal conditions. In this case, faults can be mostly isolated within the faulty feeders to improve system safety [70].

For MVDC, although having better reliability from the bipolar structure, the symmetrical bipolar DC configuration is rarely used at the MV-level due to its high cost. The most popular choices are symmetrical monopolar and asymmetrical monopolar configurations. Figure 12 shows an SST example under typical fault conditions where the symmetrical monopolar configuration is adopted on the MVDC side. Considering the possible fault propagation with the interconnection of AC and DC and forming a hybrid distribution system, grounding implementations are preferred on both the MVAC and MVDC ports, such that the fault current from either side can be largely isolated from the SST and the healthy feeders. This arrangement can also help with the DC post-fault restoration of the SST by providing the DC capacitor's close-loop discharging path.

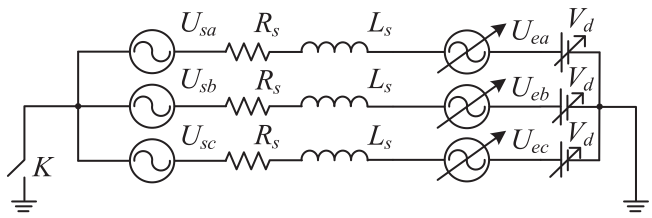

FIGURE 13 Equivalent charge and discharge circuit after DC SPG fault

To further explain, Figure 13 illustrates the post-fault AC equivalent circuit of the configuration in Figure 12(b) when the DC SPG fault occurs. In the figure, U_{sj} ($j = a,b,c$) is the AC grid voltages; U_{ej} ($j = a,b,c$) is the controllable AC port voltage of the SST; R_s and L_s are the equivalent resistance and inductance between the AC port and grid; V_d is the common-mode voltage between the DC buses, which is contributed by both switching operation of the SST and the SPG fault. If no grounding is provided on the AC side (K open), no close-loop can be formed, and the DC capacitors cannot be charged or discharged after the fault is cleared. The pole-to-ground voltages are thus still in unbalanced mode. And the system needs to be shut down and restart to restore the DC pole voltages.

DC system with asymmetrical monopolar configuration is usually adopted in railway systems accompanied by the solid grounding scheme. However, it should be noted that solid grounding is not recommended on the AC side if no interface isolation transformer is present. Otherwise, a permanent short circuit fault can be created between the AC and DC sides due to the common grounding.

3.3 | Grounding schemes for SSTs at the LV level

In designing the LV-level grounding schemes for the SSTs, ensuring personnel safety should be the priority objective. Limiting common-mode interference resulting from the SST switching operations must not be ignored since it can impose a severe influence on the connected appliances on the affected feeders. Like the MV level, elements that should be factored into consideration for the LV SST grounding design include configurations of the connected AC and DC distribution networks, topology of the SST, and the existence of the interface isolation transformer [71, 72]. In terms of network configuration, three-phase three-wire, and three-phase four-wire networks are popular in the current LVAC distribution systems. Similar to MVDC, the asymmetrical monopolar type and the symmetrical monopolar type are the preferred structures for LVDC as well considering cost and function, where the detailed configurations play an essential role in the selection of a proper grounding scheme [73]. As traditional LVAC distribution systems make up most of the current grid, grounding design for the LVDC side must consider the requirements of the AC systems to ensure consistency in grounding choices such that the relay protections can operate adequately [72]. Similar to the MV systems, if there is no interface isolation transformer at the AC port of the SST while

TABLE 2 Comparison of LV grounding systems

	IT	TT	TN	
			TN-S	TN-C
Fault current	Low	Moderate	High	High
Fault voltage	High	Low	Low	Low
Personnel safety	Good	Good	Good	Good
Property safety	Good	Moderate	Moderate	Poor
EMC	Poor	Good	Moderate	Poor
Service continuity	Good	Average	Average	Average

the LVDC side is of asymmetrical monopolar configuration, a permanent short circuit fault will happen if the solid grounding scheme is adopted on both the AC and DC sides.

Three grounding systems, namely, TN, TT, and IT are commonly defined by IEC 60364-1 for the LV level (< 1 kVAC or 1.5 kVDC) electrical network grounding in both AC and DC systems [23, 62, 74–77]. In the naming of these solutions, the first letter stands for the state of the neutral point, and the second letter defines the state of the exposed conductive parts of the electrical installations [78]. "T" indicates that the neutral point is directly connected to the ground; whereas "I" denotes that the neutral point is isolated from the ground; and "N" means that the protective line is connected to the ground via the neutral point. "N" and "PE" indicates the neutral line and the protective line, respectively. The N and PE lines can have different configurations in a TN network, including:

- TN-S: the neutral line and the protective line are separated throughout the system.
- TN-C: the neutral and protective functions are combined in a single PEN line throughout the system.
- TN-C-S: the neutral and protective functions are combined in a single conductor in a part of the system.

Unlike the TN systems, the protective grounding conductors in the TT scheme are connected to the local earth directly so that the interference caused by other appliances on the same feeder can be significantly suppressed. The IT grounding system for both LVAC and LVDC networks is illustrated where the supply sources are isolated from the earth, and all the appliances exposed are directly connected to the local earth. A comparison between these grounding options, for both LVAC and LVDC systems, is given in Table 2 in terms of electrical characteristics (fault current and fault voltage), protection (personnel and property safety), electromagnetic compatibility (EMC), and service continuity [75, 79].

The fault current and fault voltage have an opposite relationship and can be affected by the grounding impedance. IT system provides the best performance in personnel and property safety by suppressing the fault current with continued system service. However, it is associated with larger fault transient voltage and worse EMC interference since there is no grounding path in its configuration. Due to the relative larger fault current in the TT system, personnel safety can be guaranteed via fast fault detection and isolation. But the power supply will be cut, which affects the service continuity. Due to the existence of a grounding path in this case, a better EMC profile can be achieved. TN system almost shares the same features with the TT system. The personnel safety is ensured by the fast fault detection and isolation, but the EMC interference is worse than that in TT since the harmonic components may circulate via the common neutral line. The power service cannot be kept in TN due to the fault isolation. Furthermore, property safety may be affected by the large fault current. According to the above-mentioned features of the candidate grounding systems, TN-S system is usually utilised in lighting, heating, and computing centres; whereas TT system is adopted in the machines, communication systems, and premises with fire hazards; and IT systems is applied in safety systems, medical facilities, and industrial process [69].

For LVAC, on top of the above grounding choices, a possible grounding design is discussed in [80, 81], where high resistance is inserted between the transformer's neutral and the earth to cope with TOV. A trade-off should be made in the design of the resistance though to suppress flash hazard and guarantee timely tripping of the relay protections [82].

At the LVDC port, similar to the methods used in the MVDC networks in Figure 7, different grounding strategies can be applied via the neutral point, including solid, resistance, diode, and thyristor grounding schemes [83–87]. Based on [75, 83, 84, 88, 89], a summarised comparison of the features of these grounding schemes in LVDC systems is given in Table 3.

The diode and thyristor grounding arrangements can be regarded as ungrounded systems that possess almost the same features, such as lower stray current. However, high sensitivity fault detection can be achieved using the diode or thyristor to improve the system's reliability. On the other hand, these grounding schemes also have their inherent drawbacks. For example, a relatively high stray current in the diode grounding results in increased power loss, and the high common-mode interruption in the thyristor grounding deteriorates the performance of the connected appliances. The solid grounding schemes used in TT and TN systems may result in high amplitude current and cause potential damage the connected devices. Therefore, grounding resistance is applied to reduce the fault current at the cost of increased power loss.

Considering the mutual influence between the LVAC and LVDC grids under SPG fault [72], several valid AC and DC grounding strategy combinations are listed in Table 4. The fault circuit analysis and system behaviour are similar to those presented in Figure 2 for MV systems. For the cases with the IT system implemented at the LVAC port, most of the fault current will flow into the SST and back to earth via the designated grounding point on the LVDC side under the SLG fault. Likewise, most of the fault current will flow through the SST under the SPG fault if IT is chosen on the DC side.

Four combinations are not recommended from the table if asymmetrical monopolar configuration is used on the DC side. Because of the absence of isolation transformers and filters at the SST ports, these combinations can lead to permanent

TABLE 3 Comparison of the possible grounding strategies for LVDC systems

LVDC grounding strategies		Pros	Cons
IT	**Ungrounded**	• Low stray current • Less cost in the initial investment and post-fault repairment • Fault ride-through capability under SPG fault condition	• High common-mode interference • Difficult to detect and locate the fault • High risk of pole-to-pole short-circuit fault if the SPG fault does not clear in time which threatens the property safety
	Diode grounding	• Low/moderate common-mode interference	• Moderate/high stray current
	Thyristor grounding	• Low/moderate stray current	• Moderate/high common-mode interference
TT, TN	**Solid grounding**	• Low common-mode interference • Low insulation requirement • Easy to detect and locate the fault	• High stray current • Not capable of ride-through the SPG fault • High fault current on the ungrounded pole leading to high risk of damage
	Resistance grounding	• Limited fault current under SPG condition • Low insulation requirement • Fault ride-through capability under SPG fault condition	• The overcurrent protection is required on both DC buses • Susceptible to the noise and disturbances • Difficult to detect and locate the fault

TABLE 4 Recommended grounding scheme for SSTs in LV distribution systems

			SST LVDC Port		
SST LVAC Port			**Asymmetrical monopolar solidly grounded (TT or TN)**	**Symmetrical monopolar solidly grounded (TT or TN)**	**Ungrounded (IT)**
	TT	**With isolation transformer**	√	√	√
		Without isolation transformer	Not recommended for asymmetrical monopolar DC system	Not recommended for asymmetrical monopolar DC system	√
	TN	**With isolation transformer**	√	√	√
		Without isolation transformer	Not recommended for asymmetrical monopolar DC system	Not recommended for asymmetrical monopolar DC system	√
	IT	√	√	√	

short-circuit fault between the LVAC and LVDC sides. All the other listed combinations inherit the drawbacks of their constituent types. For example, any combinations including a TT or TN will produce a high amplitude fault current under both SLG and SPG conditions, which threatens personnel and appliance safety. To limit the current amplitude, grounding resistors are further needed at the grounding points at the cost of high-power loss and difficulty in detecting the fault conditions. In distribution systems with IT grounding, the high voltage will appear on the fault side, and the neutral point shift can be transferred to the healthy ports via the SST. Although the service of power may be maintained for a certain period, the connected feeders' higher insulation capability requirement increases the initial cost. Additionally, high voltage is a potential threat to personnel safety.

The grounding combinations can thereby be applied to different applications according to their characteristics under the fault conditions. The impedances of the grounding schemes implemented at AC and DC sides should be approximately equal for consistency. For critical applications that require a continuous power supply, IT grounding is preferred on both the AC and DC sides of the SST. For applications sensitive to abnormal conditions and EMI, better performance can be obtained by adopting TT or TN systems.

Another issue that should be considered at the LV level is the protective grounding design for the SSTs, especially for those with voltage level conversion capability. For example, the conventional line-frequency transformer frame's protective ground is usually connected to the neutral point of the LV functional grounding. Temporary overvoltage may be generated when phase/frame disruptive short -circuit fault occurs [23, 63], and the fault analysis is similar to that of the MV fault conditions. Hence, in future distribution networks, considerations should also be taken in the protective grounding of the SSTs due to the integration of different distribution systems. The protective grounding point of the SSTs is suggested to be separate from the functional grounding point to mitigate fault propagation. In summary, the grounding combinations with TT or IT systems are recommended for the protective grounding on the LV sides of an SST [90].

3.4 | Grounding of AC/AC and DC/DC SSTs with different voltage levels

For SSTs used to interface the same form of distribution systems, i.e. AC to AC and DC to DC, the voltage level conversion and electrical isolation are usually achieved by either line-frequency interface isolation transformers at their AC ports or the high-frequency transformers embedded in the SST converters. The grounding scheme design should be done separately for the MV and LV sides, with the detailed options being the same as the choices mentioned above.

Overall, the grounding scheme design for the SSTs should prevent the potential conflicts between the ports and the connected distribution systems. When the consistency of the grounding scheme design of the connected feeders and the SSTs' ports cannot be maintained, the protection schemes and the corresponding devices are not capable of detecting and isolating the abnormal conditions. For example, when the MVAC grid adopts low-impedance grounding scheme and the MVAC port of the SST uses high-impedance grounding arrangement, the protection schemes of the SST may not be tripped in time due to the different characteristics of the grounding schemes. On the other hand, if the consistency between the AC port and DC port with the same voltage level cannot be kept, spurious tripping will occur. For instance, the galvanic isolation of the MMC based SST shown in Table 1 is achieved by the high- or medium-frequency transformers such that the grounding scheme design for the SST can also be divided into the MV- and LV-side grounding schemes. When a high-impedance grounding scheme is used at the MVAC port and a low-impedance grounding scheme is applied at the MVDC port, conflict will occur between these two ports where the MVAC side protection schemes and devices will experience spurious tripping when the system encounters abnormal conditions. Therefore, the grounding scheme arrangement for the SSTs should be carefully designed considering multiple angles as discussed above.

4 | INCLUSION OF RELAY PROTECTION IN THE GROUNDING SCHEME DESIGN

Protection schemes in AC or DC distribution systems are generally evaluated based on four primary metrics: speed, selectivity, sensitivity, and reliability [91]. In most scenarios, protection for the distribution system and the connected electrical equipment is always done by coordinating the grounding schemes and the relay protections implemented on the adjacent feeders.

However, conventional relay protection methods and devices may not operate properly when SSTs are introduced to the distribution systems because of the changed fault characteristics [7]. Traditional relay protections are usually separately designed for AC or DC distribution systems. Due to the integration of the AC and DC grids and the mutual influence, relay protection devices will encounter more complicated abnormal conditions such as fault propagation in future distribution systems [92, 93]. The characteristics of SLG/SPG faults will be transferred to the healthy DC/AC feeders and affect the performance's corresponding relay protections.

In terms of relay protection methods, conventional relay protection devices may be tripped spuriously if directional protection is adopted when an AC side fault propagates to the DC side via the SST. This is mainly because of the possible reverse power transfer transients. Another case is that conventional relays with current sensitivity and selectivity levels will not suffice when differential protection is used. Furthermore, if distance protection is applied, the protection scope will be decreased due to the system impedance increase. The large amount of harmonic currents introduced by the transient fault propagation could cause mis-triggering of the DC relay protection devices and commutation failure if AC fault occurs.

Additionally, since the power electronic elements in the SSTs are more vulnerable and sensitive, conventional relay protection devices cannot correctly deal with the abnormal conditions [85]. Relay protection devices with higher sensitivity and selectivity are therefore necessary. The traditional protection methods [75, 94–96] should also be modified and upgraded with these new protection devices, sensors with a high sampling rate, and fast communications systems [97, 98]. For example, the traditional differential protection used in the line-frequency transformer cannot be used to protect the SSTs because of the altered fault characteristics of future distribution networks. At present, solid-state relays, such as solid-state circuit breakers (SSCB) [99–103], and advanced current limiters [100, 104, 105] shown in Figure 14, are becoming more attractive due to their fast switching speed, high reliability, capability in suppressing fault current and arc-flash, and compact size [94]. During the past decade, there was an increasing interest on the SSCBs and the current limiters with low loss, high efficiency, and fast response speed. As depicted in Figure 14(a), SSCBs generally consist of sensors, gate drivers, power semiconductors and voltage clamping circuits. Different types of SSCBs based on different power semiconductors and circuit topologies can be found in the recent articles. An IGBT based SSCB was proposed with a system voltage up to 10 kV DC and 1000 A, with an 800 ns opening time [106]. A 4.5-kV MVDC SSCB based on 15-kV SiC ETO was tested for a unidirectional circuit breaker for MVDC power distribution with a maximum turn-off current 200A [107]. Generally, the SSCBs can be categorised into three types depending on the device topologies, including the type using fully controlled switches, the type using semi-controlled switches, and

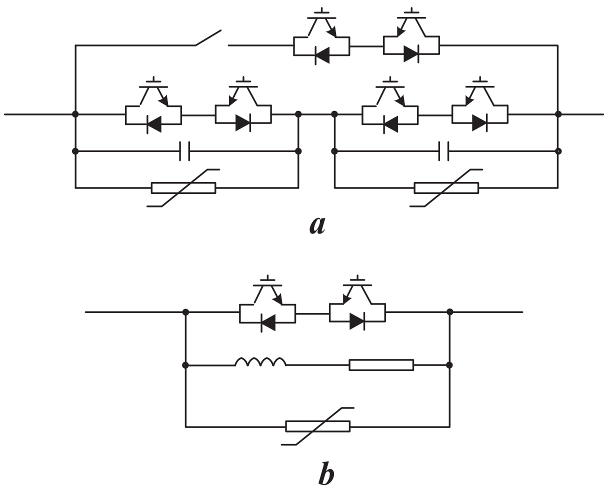

FIGURE 14 Typical relay protection devices. (a) Hybrid solid-state circuit breaker; (b) solid-state current limiter

the type with advanced topologies. Besides, the hybridisation of the mentioned SSCB topologies which shares the merits of different SSCB topologies is also possible [108]. Current limiters can be classified by their principle of operation and key technological component adopted. As shown in Figure 14(b), current limiters are usually formed by passive nonlinear elements, inductive devices, vacuum switches, and the power semiconductors as well as the superconductor topologies. Similar to the SSCBs, the hybrid topologies can be applied which shares the benefits of different topologies of the current limiters. The current limiters are divided into three types based on the detailed topologies, including the series switching-type, the bridge-type, and the resonant type [104].

These devices also come with inherent disadvantages such as high conduction loss, short device lifespan, and high cost, which hinder their widespread use. It is worth noting that some of the MMC based SSTs have intrinsic DC blocking capability owing to their specific submodule structures [109]. In MMCs with full-bridge submodules, clamp-double submodules, and three-level cross-connected submodules, the protection device such as DC circuit breakers, can be saved to further reduce the volume and investment of the system at the cost of the increased use of the power electronic elements [110]. The coordination of the relay protection and grounding scheme design of the SSTs used in the future distribution system should be comprehensively considered to improve the reliability and robustness.

5 | CHALLENGES OF THE GROUNDING SCHEME DESIGN FOR SSTS

SSTs enable the interconnection between different types of distribution networks with varying voltage levels. The grounding scheme design plays a vital role in the operation of the SSTs under different scenarios in terms of both device and personnel safety. So far, although the reliability of the traditional grounding schemes is varied and widely used in the current SST applications, these devices cannot feasibly and flexibly deal with the complicated conditions caused by the distribution system integration. Several problems are still unsolved in the grounding scheme design for the SSTs.

5.1 | Optimisation of the existing grounding schemes

The current grounding devices are bulky and heavy comparing to the SSTs, which can be reduced through optimising the size of the fundamental circuit elements, such as the reactor and the resistors.

5.2 | Advanced grounding device development

Although a resonant grounding scheme can adjust its grounding impedance among the grounding schemes, automatic impedance control is unavailable. Owing to the development of the semiconductors, the advanced grounding device equipped with solid-state switches is prominent such that the impedance can be adjusted automatically under various conditions to reduce the cost and losses. Besides, the advanced grounding devices' control should cooperate with the system fault detection algorithm to improve system safety and reliability.

5.3 | Cooperation of the grounding schemes of different SSTs

In the meshed hybrid distribution network, different SSTs are connected where the separated grounding schemes may lead to mutual influence on each other. Detailed analysis is required from the system-level in terms of the impedance sharing and fault propagation such that cooperation of the different grounding schemes can be achieved economically and efficiently by proper control.

5.4 | New testing methods and standards for grounding schemes in SSTs

Since different distribution networks are interconnected, and the whole system is becoming more complicated, a conventional testing method for specific grounding schemes may not suit the SST applications. Also, there are currently no grounding scheme design standards for SSTs. Standardisation will be necessary as SST technology continues to grow since mutual influence complications may arise due to different grounding schemes of the connected SSTs.

6 | CONCLUSION AND FUTURE TRENDS

This paper presents a comprehensive overview of grounding scheme design for SST-enabled future distribution networks.

Because of the introduction of the SSTs and the increased penetration of the distributed generations, the conventional grounding arrangements and relay protections are no longer feasible according to the higher flexibility of the future grid systems and the more complicated fault characteristics. The EMI should be carefully addressed under the normal condition such that the performance of both the SSTs and the grids can be guaranteed. The overvoltage and overcurrent under abnormal conditions need to be effectively restricted to enable the potential fault-tolerant operation of the SSTs or activate the corresponding protection schemes with the shortest response time. Thus, equipment and personnel safety can be ensured. Besides, the fault propagation among the ports of the SSTs under abnormal conditions can be significantly limited by the proper grounding scheme design to maintain the power supply in the non-faulty area.

With a thorough evaluation and comparison of existing grounding schemes used in current AC and DC distribution systems, several grounding strategy combinations are recommended considering the structure and mutual influence of the connected distribution networks, topologies of the SSTs, and the existence of the isolation transformers. Additionally, novel grounding schemes associated with solid-state devices are expected to achieve faster response time and lower interference in the future distribution grids under different operation conditions.

Moreover, to cooperate with the grounding schemes and address the challenges in fault identification and localisation, novel relay devices with faster response speed and higher sensitivity and reliability are surveyed. However, these devices are associated with high conduction loss, short lifespan, and high cost. Furthermore, due to the interconnection of the AC and DC distribution networks, the mutual influence among the ports of the SSTs under different conditions may cause false triggering of the relay protection devices. Hence, more investigations and developments of the relay protection devices and cooperation with the grounding schemes are required to improve the entire system's safety and reliability.

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APPENDIX

TABLE A.1 Comparison of grounding schemes at the MVAC port

		Large fault current group				Small fault current group			
		Solid							
MVAC neutral grounding schemes		**Undistributed**	**Distributed**	**Low resistance**	**Low reactance**	**High resistance**	**High reactance**	**Resonant**	**Ungrounded**
Ratio of symmetrical component parameters	X_0/X_1	0–1		0–10	3–10	N/A	> 10	N/A	N/A
	R_0/X_1	0–0.1		N/A	0–1	> 100	N/A	N/A	N/A
	R_0/X_0	N/A		≥ 2	N/A	≤ (-1) [56]	< 2	N/A	N/A
SLG fault current in percent of three-phase fault current ($I_{SLG}/I_{3\Phi}$)		Varies, $I_{SLG}/I_{3\Phi}$ may exceed 100%		≤ 25%	25%–100%	< 1%	< 25%	1%	1%
BIL		V_{LN}				V_{LL}			
TOV		< 1.5 p.u.		< 2.5 p.u.	< 2.3 p.u.	≤ 2.73 p.u.	≤ 2.73 p.u.	≤ 2.73 p.u.	> 3 p.u.
Common-mode interruption		High				Low			Average
Power supply continuity		No				Yes	No	Yes	Yes (conditional)
Personnel safety		Medium				Good	Medium	Good	Bad
Protection sensitivity		High				Low	High	Low	Low
Thermal stress		High				Low			Average
Countries applied		USA, Spain, UK, France	Australia, Canada, USA, Latin America	France, Spain, Belgium. Japan, Portugal, China, USA			N/A	Italy, Northern, and Eastern Europe, Israel, China	Germany, UK, Italy, Ireland, Japan, China
Relay coordination		Good		Good	Good	Excellent	Good	Excellent	Difficult
Protection sensitivity		Good		Good	Good	Average	Good	Average	Average

TABLE A.2 Comparison of grounding schemes at the MVDC port

			Resistance grounding			Solid grounding		
MVDC grounding schemes	**Ungrounded**	**Diode/thyristor grounded**	**Capacitance mid-point in symmetrical monopolar system**	**Clamped resistance in symmetrical monopolar system**	**Grounded in symmetrical bipolar system with neutral resistor**	**Asymmetrical monopolar system**	**Capacitance mid-point in symmetrical monopolar system**	**Symmetrical bipolar system**
V_n	0, U_n	0, U_n	$-U_n/2, U_n/2$	$-U_n/2, U_n/2$	$-U_n, 0, U_n$	0, U_n	$-U_n/2, U_n/2$	$-U_n, 0, U_n$
Grounding point	N/A	Single/multiple	Multiple	Multiple	Single/multiple	Single/multiple	Multiple	Single/multiple
Safety	Low	Moderate	High resistance	Low resistance		High		
			Low	High				
Fault current level	Low	Moderate	Low	High		High		
TOV	High	Moderate	High	Low		Low		
BIL	High	High	High	Low		Low		
Relay protection	Hard	Easy	Hard	Easy		Easy		
Fault tolerant operation	Yes	No	Yes	No		No		
EMI	High	Moderate	High	Low		Low		
Stray current	Very low	Moderate	Low	High		Low		
Power loss	No	No	Yes	Yes		No		