

## Article

# Applications and Implications of Wide-Bandgap Technologies in Microgrids: A Review

Daniel Burmester , Ramesh Rayudu \*  and Alan Brent 

Sustainable Energy Systems, Te Herenga Waka—Victoria University of Wellington, Kelburn, Wellington 6012, New Zealand; daniel.burmester@vuw.ac.nz (D.B.); alan.brent@vuw.ac.nz (A.B.)

\* Correspondence: ramesh.rayudu@vuw.ac.nz; Tel.: +64-4-886-5332

## Abstract

The next evolution in power electronics is being driven by wide-bandgap materials—particularly silicon carbide and gallium nitride power semiconductor devices—which increase efficiency and power density, thus ensuring their integration into high-performance systems. One system poised to receive benefits from this progression is microgrids. This paper reviews common microgrid architectures, components, voltage and power levels, and power electronics to establish where wide-bandgap materials, specifically silicon carbide and gallium nitride, may benefit current and future microgrids.

**Keywords:** microgrid; nanogrids; wide bandgap; silicon carbide; gallium nitride; power electronics

## 1. Introduction

Microgrid ( $\mu$ G) topologies, be it alternating current (AC), direct current (DC) or a hybrid of the two, rely heavily on power electronics to accentuate the benefits these power structures can offer modern power grids [1].

Defined as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid,” a microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode [2]. The application of power electronics in a  $\mu$ G structure is vast [3].

$\mu$ Gs boast the ability to implement advanced control systems to maximise the use of distributed energy resources (often renewable energy), demand-side management, grid interactions—including disconnection and autonomous operation (islanded)—grid-forming inverter technologies, multi-platform storage systems, optimisation techniques, and pricing schemes, such as peer-to-peer energy trading, among other functions [4,5].

While these operations often rely on a software layer, their implementation is dependent on the hardware. Of this hardware, power converters (including DC/DC, AC/DC, DC/AC, and AC/AC) and protection circuits depend heavily on power electronics to ensure safe and efficient operation.

In recent years, the focus of power electronics engineers has turned to wide-bandgap (and to a certain extent, ultra-wide-bandgap) electronics as the next evolution of electronically controlled switches. The advantages of wide-bandgap (WBG) materials, such as silicon carbide (SiC) and gallium nitride (GaN), are their ability to operate at higher voltages, temperatures, and frequencies, which results in higher efficiency and increased power density for circuits [6].



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Within the WBG literature, a number of review papers exist, covering topics of interest within the power electronics and power systems community. An investigation of the state-of-the-art material properties, packaging of WBG/ultra-WBG semiconductors, and figure of merit (FOM) is presented in [7–15]. The application of WBG semiconductors within power electronics is discussed in [16–20]. From here, the integration of WBG power electronics into larger systems, such as electric vehicles [21,22] and smart grids [23,24], is reviewed. However, an analysis of the literature regarding WBG in the context of microgrid topologies and applications is yet to be presented. This paper discusses the applications of WBG power electronics in the specific context of  $\mu$ G structures, highlighting where WBG power electronics will be pertinent for these multifaceted systems, and how WBG's advantages will complement future power systems.

The paper is arranged in the following manner: Section 2 presents a review of  $\mu$ G topologies, typical voltage and current levels, various conversion/protection stages, and where power electronics play a crucial role. Section 3 reviews WBG technologies and discusses their operational limits. Section 4 identifies applications within the  $\mu$ G topologies, where WBG switches are advantageous based on voltage, current, and power levels, before the paper is concluded in Section 5.

## 2. Microgrid Topologies

In this section, the structure of a  $\mu$ G will be developed and instigated, highlighting the points where power electronics, and by extension WBG semiconductors, have the potential to play an important role. While it is difficult to present an exhaustive account of all architectures within the  $\mu$ G literature, there are a multitude of generalised architecture discussion points which are useful to analyse. To inform the remainder of the section, a discussion of DC, AC and hybrid networks must first be presented.

### 2.1. AC, DC, and Hybrid Network

The long-standing argument of DC vs. AC power is still prominent in  $\mu$ G literature, with DC often promoted as “the future”, while AC is viewed as the more practical option given the current electrical infrastructure. As it stands, there is no decisive resolution to this debate. The advantages and disadvantages of each as well as a hybrid network are discussed below.

#### 2.1.1. Direct Current Verses Alternating Current

The resurgence of DC architectures in power systems has been motivated by advancements in power electronics, making it feasible to manipulate DC voltage levels efficiently [25]. This has allowed loads to utilise DC power internally, even in an AC-dominated power structure [26].

Another motivating factor is the fact that small-scale renewable energy (e.g., photovoltaics) and energy storage (e.g., battery systems), often utilised in  $\mu$ Gs, supply DC power [26]. While a DC grid would still require DC/DC conversions, in an AC grid, this DC supply/load has led to additional power stages (DC supply to AC distribution and back to DC within loads), decreasing system efficiency [26–28].

AC also introduces frequency-related difficulties, such as the need to synchronise with external grids, a reduction in “useful” line capacity due to reactive power, and additional line losses caused by the skin effect and AC harmonic oscillations [25,27,29,30]. However, AC does present “zero crossings” in its waveform, which is advantageous to protection systems, an area in which DC remains relatively complex and immature [26,31,32].

For historical reasons predating modern power electronics, AC power has long dominated electrical infrastructure. Consequently, AC  $\mu$ Gs benefit from inherent compatibility

with the existing power network, widespread availability of consumer appliances, and well-established standards [28,33].

### 2.1.2. Hybrid Network

As the name implies, hybrid  $\mu$ Gs are a combination of AC and DC grids, which allow for the advantages of both structures to be harnessed [34–36]. These advantages include the ability to integrate both AC and DC devices (generation, storage and loads) with reduced conversion stages between AC and DC, and thus increasing efficiency. Furthermore, synchronisation between generators and storage units is not required, and AC infrastructure such as transformers can be utilised to step up/down voltages [34,37–39].

While hybrid AC–DC networks offer clear advantages, there are still a number of open research challenges. Protection of the DC subsystem is still a significant concern, and power quality issues persist due to non-linear loads as well as single-phase or unbalanced loads and generators. System reliability can also be compromised by the dependence on interface power converters. Finally, the overall control complexity increases, particularly when coordinating both AC and DC subgrids during islanded operation [34,38,40].

### 2.2. Point of Common Coupling (PCC)

External to a  $\mu$ G—assuming it is not operating as a stand-alone or “off-grid” system—is the external utility grid. A  $\mu$ G interacts with this external power transmission system to export or import power.

This interaction is facilitated via the “point of common coupling (PCC)”, where a  $\mu$ G physically connects to, or disconnects from, the external grid [41]. While not strictly part of the  $\mu$ G, it is worth mentioning some of the typical characteristics of the external transmission system.

As shown in Figure 1, the external transmission system is typically either a medium-voltage (larger  $\mu$ G systems) or low-voltage (smaller  $\mu$ G systems) three-phase AC (smaller systems may be single phase) which is interfaced through a transformer, supplying the appropriate  $\mu$ G voltage. It is possible for  $\mu$ Gs to have more than one PCC; in some scenarios, they can even have multiple active connections, or for a contingency [42]. The connection for AC, DC, and hybrid  $\mu$ Gs are bidirectional and have a controlled circuit break with the ability to island the  $\mu$ G deliberately or in response to a fault. At the PCC, DC and hybrid networks are more complicated than AC, as they require a power electronic interface to the AC transmission system. This will consist of an AC-to-DC conversion while importing power, and DC-to-AC as well as a synchronisation of equipment for the export of power [43].

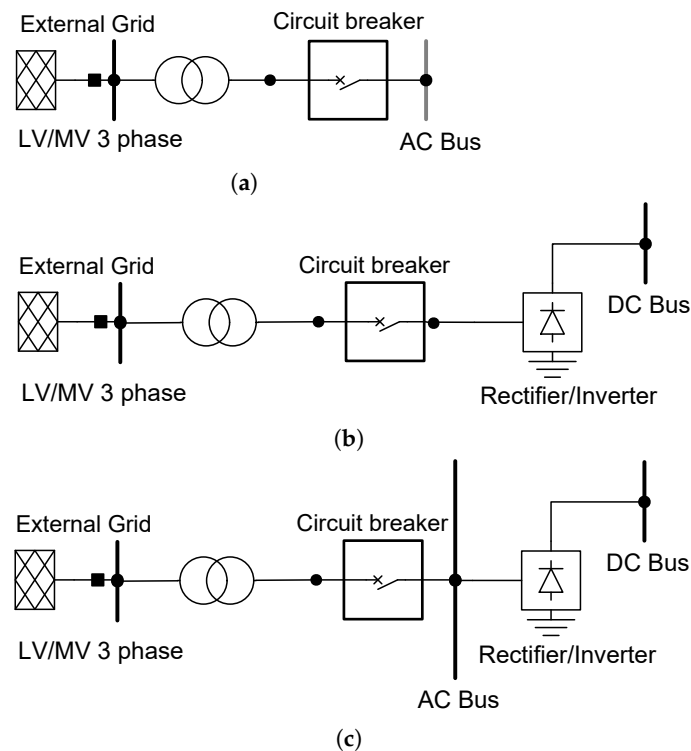
In the absence of available local generation and/or storage, the PCC must deliver all required power to the  $\mu$ G. This means that for the DC and, to a certain extent, the hybrid topologies, the PCC converter is of fundamental importance.

### 2.3. Distribution Architectures

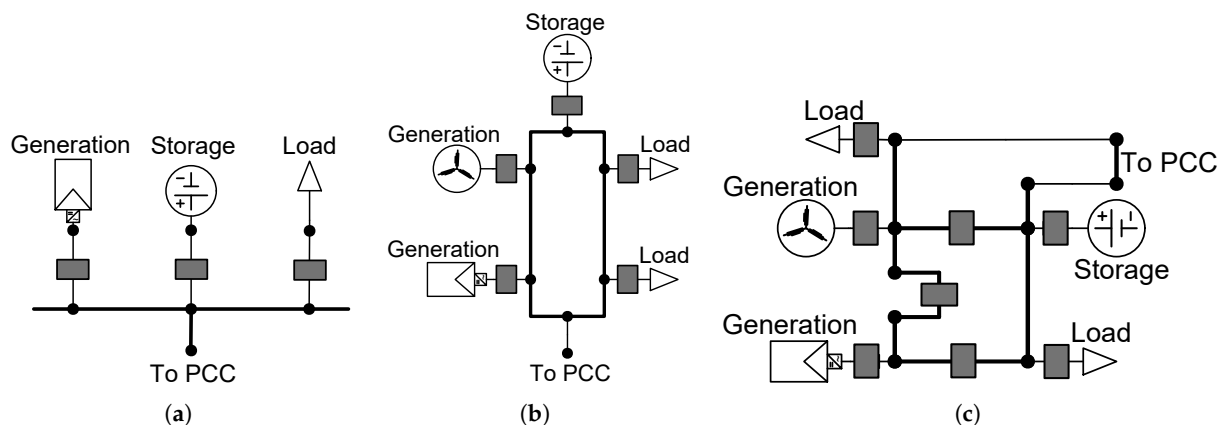
Connected to the PPC is the distribution system of the  $\mu$ G. The manner in which power is distributed within  $\mu$ Gs is of the utmost importance as it influences system cost, resilience, flexibility, control, scalability, and voltage and current magnitudes [25,31].

#### 2.3.1. Common Distribution Architectures

While niche distribution architectures exist within the  $\mu$ G literature, the commonly discussed architectures for DC, AC, and hybrid  $\mu$ Gs are “radial”, “ring”, and “mesh” networks. A single-line diagram of each architecture is shown in Figure 2, where the grey boxes represent power electronic converters which will vary depending on whether the network is DC, AC or hybrid.



**Figure 1.** Examples of AC, DC, and hybrid PCCs: (a) AC  $\mu$ G PCC. (b) DC  $\mu$ G PCC. (c) Hybrid  $\mu$ G PCC.



**Figure 2.** Common distribution architectures: (a) Radial network. (b) Ring network. (c) Mesh network.

Radial grids are characterised by a single bus or "feeder" to which generation, storage, loads and the external grid are connected. Consequently, parallel radial distribution systems also exist, which consist of more than one feeder, and are designed to increase reliability, as a single feeder has the disadvantage of a single point of failure. The radial distribution system does, however, have the advantage of simplicity and low cost.

Ring distribution systems, as the name implies, consists of a loop, to which all network elements are connected. This creates a comparatively flexible and robust distribution system when compared to the radial network, as a single fault will still allow power to be fed to loads. The drawback for this system is the increased cost of implementation and complexity.

Mesh networks are a progression of the ring distribution system, including redundant lines, which allows power to be routed through alternative feeders in the case of a failure. With the increased robustness, there is also an increase in complexity [25,29,44,45].

As suggested in [25], the various distribution architectures lend themselves to particular bus voltage levels. And while there are no real limits as to voltage levels within a  $\mu\text{G}$ , a number of accepted voltages does exist within the literature.

### 2.3.2. Commonly Discussed Bus Voltage Levels

A  $\mu\text{G}$  bus is the backbone of its distribution system. In Figure 2, the system bus is indicated by the thick black line, where generation, storage, PCC, and loads are interfaced via converters/protection (in the figure, signified by a grey box). As the name might imply, an AC  $\mu\text{G}$  will have an AC bus voltage, a DC  $\mu\text{G}$  will have a DC bus, while a hybrid system will have both an AC and DC bus. Moreover, in DC or hybrid networks, there may be a single conductor (unipolar), or positive and negative conductors (bipolar) with a ground return. In bipolar configuration, generators, loads, and storage systems can be connected either from positive to ground, ground to negative, or positive to negative, which creates additional voltage levels compared to the unipolar. This gives the bipolar configuration the advantages of increased flexibility, reliability, and safety. The bipolar does however require additional wire and is prone to voltage imbalance [30,31,46].

In AC  $\mu\text{Gs}$ , bus voltages typically reproduce the localised grid distribution voltage [44,47]. These root-mean-squared (RMS) voltages are 110–240  $V_{\text{RMS}}$  for a single-phase system and 380–400  $V_{\text{RMS}}$  for three-phase systems [47,48]. This allows the current grid infrastructure to be utilised within the AC  $\mu\text{G}$ , lowering system cost and simplifying integration.

The DC bus discussion is much more nuanced, which can be attributed to its relative infancy when compared to AC. Often, DC voltage is discussed in terms of “high” (greater than 1500 V DC), “low” (less than 1500 V DC), and “extra low” voltage (less than 120 V DC) [26]. Within these bands, a majority of the DC  $\mu\text{G}$  research sits in the low and extra low voltage bands, more specifically within the ranges discussed in Table 1.

**Table 1.** DC bus voltages utilised in  $\mu\text{Gs}$ .

| Voltage Range       | Description                                                                                                                                                                                                                                                                |
|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 12 V, 24 V and 48 V | Typically considered “short range” voltages (inefficient over long distance distribution/transmission) and are utilised in applications such as households (also known as a nanogrid [49]) and communication systems [25,47,50].                                           |
| 350 V to 450 V      | Often used in $\mu\text{Gs}$ , these DC voltage levels are selected because they provide the appropriate peak voltage required to generate 230 $V_{\text{RMS}}$ of AC power. The applications range from households, offices, and hospitals to data centres [30,47,50–52]. |
| 600 V to 900 V      | At the high end of the voltages commonly discussed in the literature with 700 V/750 V drawing a lot of attention in this band. This voltage range is used for industrial/commercial applications and transport such as shipboards [26,47,52].                              |

Bipolar DC/hybrid systems commonly utilise  $\pm 170$  V in households [30,46],  $\pm 190$  V to  $\pm 220$  V in data centres [26,46] and  $\pm 700$  V to  $\pm 750$  V is also presented for use in shipboards and last mile power distribution [26,52].

The implications of voltage levels, with regard to power (and in turn current), is also an important factor when determining efficient and safe operation within a  $\mu\text{G}$ .

### 2.3.3. Power Magnitudes

In AC  $\mu\text{Gs}$ , the limits are reasonably well defined by grid/wiring standards. The research presented in [53] gives an in-depth overview of the standards applicable to AC

$\mu$ Gs. The International Electrotechnical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE) both have international standards on  $\mu$ G operation, while a number of countries have their variations of these.

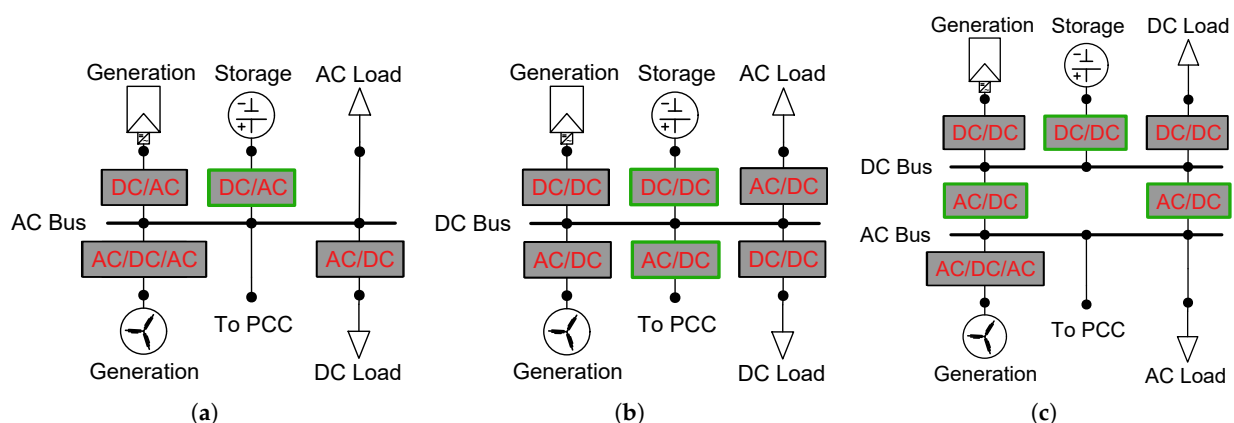
For DC  $\mu$ Gs, the power limits are less defined. However, within the literature, power ratings are often defined by voltage bands. Less than 48 V operates in the hundreds of W range (1 kW suggested as the upper limit), while 120 V to 230 V operates in the low thousands of W range (6 kW suggested as the upper limit). Above this, 350 V to 450 V operates in the tens to low hundreds of kW range (500 kW suggested as the upper limit). At the upper end, 600 V to 900 V operates at less than 1 MW, while greater than 1000 V operates in the tens of MW range [26,47].

It is common to have multiple voltage levels within a  $\mu$ G, as generators and/or storage units may have one or multiple output voltages, different to the bus voltage. The voltage may be modulated again to meet the demands of various loads in the system [50]. This function, among others (protection, power quality, supply optimisation), is performed by power electronic converters.

#### 2.4. Power Conversion

An AC, DC, and hybrid radial  $\mu$ G network is shown in Figure 3, where the prevalence of power converters is apparent. As in Figure 2, grey boxes indicate power conversion, but with the “type” of conversion notated and the bidirectional nature of certain converters marked with a green border. AC loads, in this context, are assumed to be loads that can operate directly off AC power (for example, resistive loads or certain motors), but it should be noted that often AC loads have further conversion to DC internal to the load. DC loads may also operate directly off the bus voltage, so in some cases the DC load converter may not be required.

In AC networks, AC-to-DC and DC-to-AC conversion is dominant, while in DC networks, DC-to-DC converters are more prevalent and the hybrid network utilises a mixture of conversion types. It should be noted that bidirectional AC-to-DC conversion in DC and hybrid networks plays a crucial role, facilitating the PCC in the former and allowing power sharing between AC and DC buses in the latter. Below, common topologies utilised in  $\mu$ Gs are presented in order to capture an overview of potential WBG applications:



**Figure 3.** AC, DC and hybrid converter implementations: (a) AC network converters. (b) DC network converters. (c) Hybrid network converters

- AC to DC [54–56]: This conversion is utilised by DC  $\mu$ Gs in grid-connected mode and when receiving power from wind turbines or other AC generators. In an AC  $\mu$ G, it is

typically used when supplying DC loads and storage elements, while in a hybrid  $\mu$ G it may also interface the AC and DC buses.

- Rectifier circuits can be passive or active (uncontrolled or controlled switches, respectively), single-phase or three-phase (depending on the upstream AC configuration), uni- or bidirectional, and often require power factor correction (PFC) to be considered. Passive/Active determines the switch components utilised within the rectifier. Common passive switches are diodes, while active ones include thyristor, metal oxide field effect transistor (MOSFET), and insulated-gate bipolar transistor (IGBT). Single/Three phase will determine the number of switches utilised in the rectifier. A full-bridge style converter is common in single-phase applications (four switches), while in three-phase circuits, two-level (typically six switches), three-level (typically twelve switches) or Vienna (six passive, six active switches) rectifiers are common. In three-phase systems, two-level and three-level converters are bidirectional topologies, while Vienna rectifiers are unidirectional. For single-phase ones, an active full-bridge converter can be bidirectional. It is common to smooth the output of a rectifier with a filter capacitor; this creates a harmonic distortion on the AC side of the circuit (due to the charging/discharging of the capacitor) which creates the need for power factor correction. Power factor correction can be achieved with active rectifiers (or the addition of controlled switches in a passive circuit) and the addition of passive filter components (inductor, capacitor).
- DC to DC [54,57–63]: Utilised in AC, DC, and hybrid  $\mu$ Gs (though more commonly in the latter two topologies), DC/DC converters can be found in many and diverse applications, such as control/interface generators, storage units, in the manipulation of voltages to and in loads, connecting system buses, etc.
  - A buck converter is used to step down a DC voltage. It can either be asynchronous, which utilises an active switch (MOSFET or IGBT) and a diode, or synchronous, which utilises two active switches. Buck converters can be used to interface generators, such as PV and wind turbines with the DC bus. They can also be used to step down bus voltages for loads requiring low-voltage DC.
  - A boost converter is used to step up a DC voltage. In its most basic form, the boost converter consists of a controlled switch and a diode. In high-power and/or high-current applications, “interleaved” topologies are often applied. The interleaved boost converter can have an arbitrary number of levels, with each new level adding an additional controlled switch (two levels, and to a certain extent three levels are common in the literature). It is also not uncommon, in high-voltage applications, to cascade boost converters. A somewhat similar approach to interleaved boost converters is the three-state switching cell (3SSC boost converter). Voltage multiplier circuits are utilised in the 3SSC, which results in an increased number of passive and/or active switches. 3SSC converters can also be designed to operate bidirectionally.

Conventional cascaded boost converters would see an increase in passive and active switches (an extra passive and active switch per boost converter). However, variations do exist to reduce the number of switches and improve characteristics. Another approach for high-voltage applications is “switched capacitor” boost converters. These topologies charge capacitors and connect them in series to be used as voltage sources. The number of capacitors utilised will determine the number of active and passive switches; typically two diodes and one active switch per capacitor though variations exist. Boost converters, like buck converters, can be used to interface generators such as PV and wind turbines with the  $\mu$ G bus,

as well as energy storage units in the case of bidirectional topologies. Boost converters excel when a large step up in voltage is required.

- Buck-boost converters, as the name might suggest, are capable of producing an output voltage that is either higher or lower in magnitude than the input voltage. The traditional buck-boost converter consists of an active and passive switch, with an inverted DC output voltage (polarity opposite to the input voltage). Common variations of the traditional buck-boost converter include the single-ended primary inductor converter (SEPIC), Cúk, and ZETA, which all add additional reactive components to the topology to achieve improved characteristics, but maintain the single active and passive switch. Buck-boost converter variations are often used in PV applications (for example, maximum power point tracking) where the ability to step up or down the input voltage is advantageous. For applications such as battery charging, bidirectional converters are required. Buck-boost converters also come in bidirectional topologies. For the basic buck converter, this can be achieved by replacing the passive switch with an active switch. Full-bridge converters, discussed in detail below, can also be utilised as a bidirectional buck-boost converter, utilising eight active switches (two full-bridge converters connected via a transformer). Interleaved bidirectional buck-boost converter topologies are also discussed in the literature, again taking the form of full-bridge converters, with eight controlled switches being utilised.
- A flyback converter, unlike the conventional buck, boost and buck-boost converters, is an “isolated” DC-to-DC converter. It utilises a transformer (creating the isolation), an active switch, and a diode, and is used for low-power applications. Flyback converters can be designed to either step up or down their output voltage, but much like a buck-boost converter, the output voltage polarity is inverted when compared to the input.
- The dual-active-bridge (DAB) converter is an isolated, bidirectional DC-AC-DC converter capable of operating in high-voltage, high-power applications and buck-boost mode. The conventional DAB converter consists of two full-bridge converters, connected via a high-frequency transformer, meaning a total of eight active switches are utilised. The DAB converter can be interleaved to achieve a large voltage difference ratio between the input and output voltage, increasing the number of switches by eight with each stage. The DAB converter is ideal for battery charging applications and electric vehicle charging, and can be used to interface DC generators with the bus.
- Resonant LLC converters are an isolated DC-to-DC converter that consists of three main building blocks: square wave generation, resonant network, and rectifier network. The square wave generator creates a square wave of 50% duty cycle for the resonant circuit. The resonant circuit is made up of a high-frequency transformer and resonant capacitor. The high-frequency resonance is smoothed to DC by the rectifier circuit and smoothing capacitor. The resonant LLC converter boasts zero-voltage turn on, zero-current turn off, high efficiency, high energy density, low-voltage stress, and a wide output range. It is used in a wide variety of applications, including electric vehicle charging, photovoltaic systems, industrial applications, and lighting.
- DC to AC [64–68]: This conversion is common in AC and hybrid  $\mu$ Gs to interface DC elements, such as PV panels and energy storage units, with the AC bus. In DC  $\mu$ Gs, it is essential for grid connection and interfacing AC loads with the DC bus.
  - The full-bridge, H bridge or voltage-source inverter is a common topology discussed in the  $\mu$ G literature. It is equally labelled current-source or Z-source

with a change in reactive components on the DC source side. It is considered a current-source converter when the DC source has an inductor rather than a voltage-source capacitor, and it becomes a Z-source converter when an inductor/capacitor network is employed. In its most basic form (single phase), it consists of four controlled switches (half-bridge topologies also exist, consisting of only two switches, though are not often referred to in the  $\mu$ G literature), while a three-phase one uses two controlled switches on each phase (six switches in total). The full-bridge inverter can operate in bidirectional mode, making it capable of charging and discharging energy storage and interacting with the grid. A “neutral point” can be created through the use of large capacitors, or alternatively, controlled switches can be utilised to effectively handle the unbalanced loads. It should be noted that it is also not unusual to use a full-bridge converter for DC-DC conversion, demonstrating the versatility of this converter topology.

- To avoid the losses and stresses associated with high-frequency switching (as is the case with full-bridge inverters), multilevel inverters are an alternative solution for DC-to-AC conversion. There are three main varieties of multilevel inverter (MLI) topologies: diode-clamped (which utilises diodes to create a neutral point), capacitor-clamped (capacitors create the neutral point), and cascaded H bridge (which consists of full-bridge converters cascaded). The MLI creates a sinusoidal output through voltage “levels”, with the number of levels corresponding to the number of discrete voltages that make up the sinusoid (the three levels have three voltages,  $+V_{DC}$ , 0 and  $-V_{DC}$ , which create a sinewave). As the number of levels increase, so do the number of required switches. An  $n$ -level diode clamped inverter requires  $2(n - 1)$  active switches and  $(n - 1)(n - 2)$  clamping diodes, a capacitor-clamped inverter requires  $(n - 1)$  active switches, while a cascaded H bridge requires  $(n - 1)/2$  H bridges.
- Flyback microinverters create a galvanic isolation through the use of a transformer in either single-stage or multistage topologies. The multistage consists of an isolated DC-to-DC converter in series with a DC-to-AC stage, while the single stage will convert DC to AC directly. The multistage converter will generally have a full-bridge output with 4 switches (passive or active), and a boost or buck-boost-style DC-to-DC converter commonly consisting of two to four switches (usually active). Single stage can be broken down further in to single or interleaved topologies. These single-stage topologies vary greatly, in terms of switch count, from three active and two passive switches, to as many as nine active and nine passive switches (the former being a single-stage single-flyback inverter, while the latter being a three-stage inverter with soft-switching). Microinverters are commonly used to interface PV strings with the  $\mu$ G.
- AC to AC [3,69–71]: This stage is typically handled by transformers, however, converters that can directly connect AC to AC with the ability to control phase, magnitude, and frequency for the output voltage do exist.
  - Matrix converters rely on a controlled bidirectional switch, typically consisting of two parallel circuits made up of a controlled switch in series with a diode. Traditionally, the topology resembles a full bridge; however, due to the bidirectional switches, rather than four switches utilised by the full bridge, a matrix converter uses eight active and eight passive switches (single phase). For a three-phase matrix converter, each phase consists of three bidirectional switches per phase (nine total, equalling eighteen controlled switches and eighteen diodes). Due to the high component count, attempts have been made to reduce the number of switches with the Sparse Matrix Converter (SMC), the Very Sparse Matrix Con-

verter (VSMC), and the Ultra Sparse Matrix Converter (USMC). These topologies reduce the switch count to fifteen controlled and eighteen diodes for the SMC, twelve controlled switches and thirty diodes for the VSMC, and nine controlled switches and eighteen diodes for the USMC. Matrix converters have a high power density and are bidirectional, allowing them to interface AC  $\mu$ Gs with an external AC grid.

- A cycloconverter is a mature technology utilised in cement and steel rolling mills and aircraft/naval applications, but is not regularly discussed in regard to  $\mu$ Gs, and so will not be discussed in detail.
- One item of hardware that does not fall neatly in to the above categories is a solid-state transformer (SST). While AC-to-AC conversion is often the focus, SSTs consist of multiple conversion stages, of which each stage can be utilised (low- and medium-voltage DC and AC). SSTs are designed to replace bulky, voltage controlled, traditional transformers and introduce advantages of power electronics [72]. Being an active research space, not only are SSTs evolving, but a wide range of topologies also exist. In [73], SST topologies are discussed in detail, presenting the different stages, types, voltage/power levels, and applications. Single-step, two-step, and three-step topologies exist, of which the three-step has emerged as the preferred topology [72]. The three-step topology consists of a AC/DC stage, where medium AC voltage is converted to DC; a DC/DC converter is then utilised to produce low-voltage DC, before a DC/AC converter is used to create low-voltage AC [72]. In a  $\mu$ G, the SST can facilitate bidirectional power flow when connecting the  $\mu$ G with an external grid; moreover, the DC link can be utilised in the  $\mu$ G distribution system [73].

Interfaced to the  $\mu$ G network via power electronic converters are a diverse collection of generation, storage, and loads. The following section captures key characteristics of each one.

## 2.5. Generation, Storage, and Loads

As per the  $\mu$ G definition, localised generation is essential, often consisting of, but not exclusively, renewable energy-based generation. Common forms of renewable energy generation discussed within the  $\mu$ G literature are presented in Table 2, along with common non-renewable forms of generation which should, in the current climate, be considered a legacy, but are still present [29,33,74–77].

Of the above forms of generation, PV and wind turbines are commonly discussed in the literature, having convenient and accessible renewable energy sources (particularly in urban environments). Typically, these renewable energy generators operate at either DC or variable-frequency AC (rectified to DC). Without additional storage, these generators act as a current source, limited by environmental conditions. Due to this variability in output power, they are categorised as “non-dispatchable”, and require dispatchable generation, an external grid, or an energy storage medium to supplement their operation [78].

**Table 2.**  $\mu$ G generation technologies.

| Renewable                      | Non-Renewable                        |
|--------------------------------|--------------------------------------|
| Solar photovoltaic (PV) panels | Diesel- or gas-reciprocating engines |
| Wind turbines                  | Diesel or gas turbine                |
| Low-head hydro                 | Propane or natural gas micro-turbine |
| Geothermal                     |                                      |
| Tidal/wave                     |                                      |
| Biomass and biogas             |                                      |

An advantage of non-renewable generation is that it is considered dispatchable generation [79]. While this makes for a “well-behaved” power system, non-renewable generation has a negative impact on the environment.

### 2.5.1. Storage Systems

Within the  $\mu$ G system, storage has multiple functions. Not only is it utilised for energy storage to supplement renewable energy resources, but it also plays a vital role in system stability. For the former, storage is used traditionally, charged when surplus generation is present, and discharged when required. For stability purposes, storage allows inverter-based resources to participate in power quality regulation, maintaining frequency and voltage when reactive power is required and creating false inertia, a metric allowing a power system to ride through faults (typically supplied by the mechanical momentum of large turbines, also known as spinning reserves) [33,75]. The storage technologies and battery chemistries discussed within the  $\mu$ G literature are presented in Table 3 [33,74,75,80].

**Table 3.**  $\mu$ G storage technologies and battery chemistries.

| Storage Technologies                         | Battery Chemistries |
|----------------------------------------------|---------------------|
| Compressed air                               | Lithium-ion         |
| Pumped hydroelectric                         | Lead-acid           |
| Thermal energy storage                       | Fuel cell           |
| Capacitor banks (typically super capacitors) | Flow battery        |
| Flywheels                                    | Sodium–sulphur      |
| Superconducting magnetic energy storage      | Nickel–cadmium      |
| Electric vehicle (EV)                        |                     |

### 2.5.2. System Loads

The flexibility and modularity of  $\mu$ Gs allows them to be used in diverse settings, from shipboards to satellites. This, of course, means the loads presented to a  $\mu$ G also vary significantly, and the structure must be designed to be accommodating.

Within  $\mu$ G structures, loads are categorised into “industrial” and “residential” [25,29].

There are, however, some edge cases which do not fit neatly into “industrial” or “residential” (some of which are labelled “commercial”), but often share similarities with both/either (and indeed in some cases are a combination). This reflects the flexibility and potential of  $\mu$ Gs. Examples of each category of load is outlined in Table 4 [25,30,46,47,81–84].

**Table 4.** Load categories found in  $\mu$ Gs.

| Industrial                                        | Residential       | Other             |
|---------------------------------------------------|-------------------|-------------------|
| Oil refineries                                    | Home appliances   | Data centres      |
| Computer numerical control (CNC) machines         | Lighting          | Electric ships    |
| Stone crushing equipment (crusher, conveyor etc.) | Electric vehicles | Satellites        |
| Steel mills                                       | Water heating     | Electric aircraft |

Another discussion point is the “flexibility” of loads within a  $\mu$ G system. Loads can be classified as either critical/sensitive or noncritical loads [29]. As the name may imply, critical loads have very little flexibility and require uninterrupted power during their time of use. Noncritical loads on the other hand add a level of flexibility that can be advantageous to system control and, in turn, stability, allowing for demand-side management (balancing supply and demand). Noncritical loads are often thermal loads, which have slow dynamics, and devices such as EVs, which will certainly play a major role in the future power grid.

### 2.5.3. Generation, Storage, and Load Voltage Levels

A generator or storage unit connects to a  $\mu$ G bus with a converter and/or protection circuitry [80,85,86]. On the generator/storage side of the converter, the voltage level is determined by the voltage magnitude of the installed generator/storage, and/or series/parallel connection of the source. The voltage level should be designed to maximise system efficiency and connectivity. While this series/parallel connection is typically created by discrete voltage levels (for example, in steps of 12 V or 24 V), the generator output voltage can be adjusted to an appropriate voltage level to interface with the system bus.

Much like the bus voltages, loads need to be discussed separately for AC, DC, and hybrid systems. In AC systems, it is sensible to run loads at the country's grid voltage, such as 120 V or 230 V AC [30]. This minimises costs for the consumer by allowing standard household loads to be utilised.

One of the advantages of DC  $\mu$ Gs is the reduced conversions between AC and DC, increasing efficiency. This means loads are operated at DC voltages and while any voltage could technically work, there are a few commonly used voltages as presented in Table 5 [25,26,47,50,52].

**Table 5.** Load voltages utilised in DC  $\mu$ Gs.

| Voltage Range        | Application                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 12 V, 24 V, and 48 V | Often used to power household appliances, as 12 V and 24 V are common in vehicles such as cars, trucks and caravans, off-the-shelf devices are available in these DC voltage ranges. Items such as laptops utilise DC voltages in this range; under the current AC-based infrastructure, they rely on an AC/DC converter, but they can also be powered directly from a DC supply. 48 V is used in the communication and networking industry, and a number of loads, such as lighting, water pumps, air conditioning, etc., can operate in this band. These loads may interface with higher bus voltages via a DC/DC converter. |
| 200 V to 380 V       | Utilised for higher-current applications such as electric vehicle charging, induction cooking, and variable speed drives for washing machines, dryers, and air-conditioning units.                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| Higher voltages      | Less commonly discussed in terms of loads, but are utilised in transport such as trains as well as in industry and high-power applications.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |

Within a  $\mu$ G, in order to supply loads appropriately, secure the safe and correct operation of generators, and ensure system efficiency, power quality and protection hardware must be employed. In smaller grids with little or no inertia, high penetration of intermittent renewable energy, and inverter-based resource, this is particularly important.

## 2.6. Power Quality and Protection Systems

Power quality and protection systems are an integral part of any power system, but arguably more so in structures like  $\mu$ Gs. Here, the system is typically dominated by renewable generation, and often sources that do not offer the grid traditional inertia, AC or DC voltages and load fluctuations.

### 2.6.1. Power Quality

Power quality issues within a  $\mu$ G cover a wide range of phenomena in both/either AC and/or DC systems. A brief description of the power quality issues faced by  $\mu$ Gs is presented in Table 6 [87].

While historically conventional solutions (such as passive inductor/capacitor filters, capacitor banks, on-load tap changer, etc.) have been used to mitigate harmonics and improve the power factor (and in some cases still are), these solutions are being replaced by more flexible power electronic-based systems [88]. The relevant power electronics solutions are presented in Table 7 [87–89].

**Table 6.** An overview of power quality issues faced by  $\mu$ Gs.

| Issue                                                    | Description                                                                                                                                                                                                                                                                                                          |
|----------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Voltage sags (AC and DC)                                 | A dip in the average voltage for DC and RMS voltage for AC systems. This can cause disturbances in an electric motor (torque and speed) and in sensitive equipment.                                                                                                                                                  |
| Voltage fluctuations (AC and DC)                         | Occur due to a large change in source/load balance (and lightening strikes), and can cause lighting to flicker and sensitive loads to fail.                                                                                                                                                                          |
| Transient over-voltages and in-rush currents (AC and DC) | Short events where voltage and/or current will increase. This can be caused in AC systems by energising a transformer, and in DC by charging a bus capacitor. These events may also be caused by a lightning strike.                                                                                                 |
| Harmonics and inter-harmonics (AC and DC)                | In an AC system, they are either integer (harmonics) or non-integer (inter-harmonics) multiples of the system's fundamental frequency, while in a DC system, they are typically associated with the switching frequency. Harmonics can cause heating in transmission lines, power losses, and equipment malfunction. |
| System Unbalance (AC)                                    | When three-phase voltage and current wave-forms are not uniform across the three phases (equal amplitude and 120° phase difference). This can cause increased losses, temperature increase in motors, and disturbances on the negative and/or zero sequence.                                                         |
| Frequency variation of the AC supply voltage (AC)        | Caused by disparity in power generation and consumption. It can cause issues in motors, transformers, and other electrical equipment.                                                                                                                                                                                |
| Low power factor (AC)                                    | When large amounts of reactive power is present in an AC system. It is caused by reactive components (inductive/capacitive elements present) in the system and takes up valuable capacity of distribution lines; the higher the reactive power, the higher the voltage drop on the line.                             |

**Table 7.** An overview of power quality solutions for  $\mu$ Gs.

| Solution                                 | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dynamic voltage restorer (DVR)           | Used to mitigate voltage sags and harmonics. Its main components are a DC power source (storage unit), an inverter, an injection transformer and a passive filter [90].                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Static synchronous compensator (STATCOM) | Distribution STATCOM (D-STATCOM) is used to manage reactive power and voltage regulation. STATCOMs (and D-STATCOMs) fall into a larger group of technologies called flexible alternating current transmission system (FACTS) and distribution flexible alternating current transmission system (D-FACTS) designed to strengthen power quality. STATCOMs (and D-STATCOMs) consist of the voltage-source converter, connected in shunt via a reactive filter (inductors) to an AC network [91–93].                                                                                                                                                            |
| Static var compensators (SVC)            | Thought of as more of a “classical” power quality compensator. While they have the ability to reduce temporary over-voltages, dampen subsynchronous resonance, improve transient stability, correct power factor and regulate system voltages, they have the disadvantage of having a slow response, limited bandwidth and generating current harmonics. For this reason, although a higher cost is involved (and increased complexity), devices such as STATCOMs (and D-STATCOMs) are now in favour. SVCs generally consist of a thyristor-controlled reactor (TCR) and/or thyristor-switched capacitor (TSC), and can also have harmonic filters [94,95]. |
| Active power filter (APF)                | Connected in either shunt (current compensation) or series (voltage compensation) mode, the APF is used to manage harmonics created by load nonlinearities (particularly switching noise). The shunt and series APFs cancel the unwanted harmonics by injecting a current (shunt) or voltage (series) 180° out of phase of the unwanted harmonics, and of equal magnitude, cancelling their presence within the $\mu$ G. Both the shunt and series utilise a voltage-source inverter in their operation [96,97].                                                                                                                                            |

Table 7. Cont.

| Solution                                       | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| A unified power quality conditioner (UPQC)     | A device consisting (most commonly) of two voltage-source converters (VSCs), one connected in series, acting as a voltage-source inverter, while the other is connected in shunt, acting as a current-source inverter. Using its filtering capabilities, the UPQC can work to mitigate power quality issues such as harmonics, reactive power, voltage sags/swells, and flicker protecting sensitive loads [89,98].                                                                                                                                                                                                                                                                                                                                                  |
| Unified power flow controller (UPFC)           | The UPFC acts to control a $\mu$ G's transmission voltage, impedance, and active/reactive power. Much like the UPQC, the UPFC consists of two VSCs interconnected through a DC link, and interacting with the $\mu$ G in both series and shunt configuration (one VSC series, the other shunt) [99,100].                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| Universal active power line conditioner (UPLC) | Takes the same physical structure as the UPQC and UPFC, and implements a control system that combines the functionality of the two [101–103].                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| Series voltage regulator (SVR)                 | Used in DC $\mu$ G, much like DVR in an AC $\mu$ G, to mitigate the voltage sags (or droops) which can be caused by transmission line resistance and impact supply droop control, decreasing the accuracy of power sharing. A SVR typically consists of a dual-active-bridge (DAB) converter and full-bridge DC-DC converter connected in series with the DC grid [86,104,105].                                                                                                                                                                                                                                                                                                                                                                                      |
| Voltage balancer                               | Used in a bipolar DC microgrid to mitigate voltage imbalance caused by asymmetric consumption. In a bipolar DC $\mu$ G, the voltage between positive and neutral should be the same in magnitude as the voltage between negative and neutral (for example, $\pm 170$ V). An imbalance sees a shift away from this normal operating condition. Voltage balancers can be either centralised or distributed and consist of DC-DC converters, typically buck-boost variations such as Buck-boost, Ćuk, single-ended primary-inductor converter (SEPIC), ZETA, as well as multilevel converters. Converters with galvanic isolation have also been utilised; these are often variations of the DAB converter (DAB, multilevel DABs, dual-active-half-bridge (DAHb)) [46]. |

### 2.6.2. Protection

To ensure the safe operation of a  $\mu$ G, system faults such as overcurrent (caused by lightning strikes or low/high impedance shorts) must be protected against. In an AC system, conventional protection techniques are well understood. For example, overcurrent relays (OCRs) trip if the current in the system is above some predefined value (time delays may be included); directional OCRs improve on the traditional OCRs by introducing the ability to operate with the bidirectional current; distance relays observe the impedance in a section of the network to identify the location of a fault and respond by sending a trip signal to the appropriate circuit breaker; and differential relays compare the input and output current of a particular device (transformer, transmission line, etc.) and their difference to predetermined values in order to identify a fault, over/under voltage (OV, UV) and over/under frequency (OF, UF), monitoring the voltage or frequency in a network to ensure the network operates within certain bounds and ensures the stability of a network [106].

There are also techniques in AC  $\mu$ G protection that utilise power electronics. A “fault current limiter (FCL)” creates a high impedance in the case of a fault and zero impedance otherwise [107]. A solid-state FCL will operate with a bypass switch (typically a thyristor), conducting under normal conditions, which is turned off during a fault, transferring the fault current to a shunt reactor circuit [108].

Power electronics are far more prevalent in DC  $\mu$ G protection, where protection is complicated and relatively immature. Unlike AC  $\mu$ Gs, DC systems do not have zero voltage/current crossings, and this constant voltage/current can cause arcing in a standard mechanical switch (though mechanical applications still exist) [109]. This has resulted in the creation of the following [109–111]:

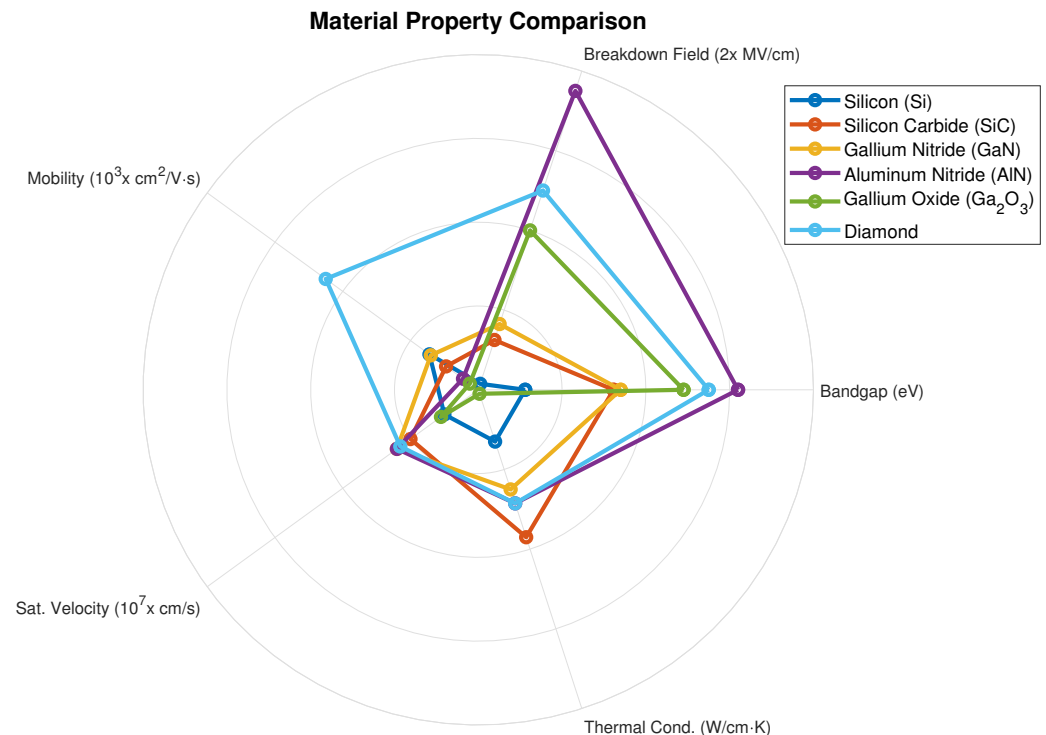
- Solid-state circuit breakers (SSCBs) utilise a series of connected semiconductors to replace the traditional mechanical switch in order to break the flow of current in a fault scenario. It requires low conduction losses and a fast response time.
- Z-source circuit breaker (ZSCB) consists of a Silicon-Controlled Rectifier (SCR), Z-source capacitors and a diode/inductor circuit. In the case of a fault, the current through the series inductor remains constant, which in turn ensures the Z-source capacitors match the inductor current, which creates a situation where the current through the SCR approaches zero, switching it off (an SCR will disengage when its current drops to zero).
- Hybrid (mechanical and solid-state) breakers (HBCBs) are designed to maximise the benefits of both mechanical and solid-state breakers, while reducing the disadvantages. The HBCB consists of three parallel elements, which can be connected in series with a residual circuit breaker (RCB) and a current limiting reactor (CLR). The parallel elements that make up the main circuit are a mechanical switch, a solid-state switch, and a metal oxide varistor (MOV). Under normal operating conditions, the current flows through the mechanical switch. In the event of a fault, the mechanical switch sends a signal to the solid-state switch to turn on and begins to open. The solid-state switch conducts until the mechanical switch has the ability to fully block (at which point the solid-state switch disengages). A variation of this circuit, developed by ABB, is a proactive hybrid DC circuit breaker, which builds on the HBCB abilities, but adds a commutation switch in series with the mechanical switch.

### 3. Wide-Bandgap Technologies

Silicon (Si) has been, and still is, the dominating semiconducting material used for electronic components such as MOSFETs, IGBTs, diodes and integrated circuits [7]. As the limits of what Si devices can achieve are reached, naturally, researchers and manufacturers have looked for alternative solutions to gain higher performance. WBG materials is one such solution.

Bandgap refers to the energy required for an electron to jump from the valence band to the conduction band within a semiconducting material [18]. For Si, a bandgap of 1.1 electron volts (eV) applies, while wide-bandgap materials generally require between 2 and 4 eVs [112]. Being used as a switch, the properties of WBG materials have advantages of operating at higher voltages, switching frequencies, temperatures, and lower leakage current when compared to Si [113]. While still in their infancy compared to Si, researchers have addressed a number of challenges that plagued the early uptake of WBG switches. Therefore, there are still a number of challenges to overcome, including reliability, a lack of standardisation, system integration, device fabrication, and cost (more details in Section 4) [114].

As an extremely dynamic research field, many WBG materials are being explored for their potential benefits; for example, silicon carbide (SiC) and gallium nitride (GaN), aluminum nitride (AlN), gallium oxide (Ga<sub>2</sub>O<sub>3</sub>) and diamond, with the latter three being considered ultra-wide-bandgap. Figure 4 displays the comparative characteristics of each material [115]. Currently, the two common commerciality available WBG materials are silicon carbide (SiC) and gallium nitride (GaN), which will be the focus of this discussion [113].



**Figure 4.** Comparative characteristics of materials.

### 3.1. Silicon Carbide

SiC exists in over 250 polytypes, of which 3C-SiC, 4H-SiC, and 6H-SiC have received the most attention, with the latter two used in power electronic devices [18]. Commercially available silicon carbide devices come in the form of diodes, thyristors, bipolar junction transistors (BJTs), junction field effect transistors (JFETs), and MOSFETs. The following paragraphs outline the characteristics discussed in [116–126].

MOSFETs are commonly available in 1.2 kV and 1.7 kV, but can also be found in 3.3 kV [127]. The current ratings of 100 A to 150 A is common, with modules (typically half-bridge configuration) reaching up to 800 A (at 3.3 kV). This means the power rating for commonly available SiC MOSFETs sit comfortably in the 100 kW to 200 kW range, with “modules” (series and/or parallel connected MOSFETs in one package) pushing into the low-megaWatt range (approximately 2.5 MW). Switching and conduction characteristics are also important, as they determine losses in the switch or module. At 25 °C, the on resistance in the conduction path of the MOSFET ( $R_{DS(ON)}$ ) can vary from less than 10 mΩ (7 mΩ, 650 V at 50 A [122]) to above 1000 mΩ (1300 mΩ, 1700 V at 7 A [119]). Rise times can be less than 1 ns [128], while the tens of nanosecond range is common (ten to sixty nS is common in datasheets), with rise times reaching up to the hundreds of nanoseconds. Fall time is generally in the tens of nanoseconds, again reaching hundreds in some cases. It should be noted that fast rise and fall times are only beneficial if the correct driving circuitry is implemented.

Diodes were the first SiC power device to be successfully commercialised. SiC diodes operate in a very similar voltage range to SiC MOSFETs with 1.2 kV to 1.7 kV being very common, and 3.3 kV available [129]. The current ranges from less than 1 A, to 150 A. The SiC diode excels in reverse recovery time, which is theoretically zero, though in practice less than 20 nS [130]. This implies, for an SiC Schottky diode, losses are almost independent of switching frequency. The forward voltage drop of these devices, which is responsible for conduction losses, is generally between 1 V and 2 V.

SiC thyristors are commercially available, though not as commonly discussed as MOSFETs and diodes in the  $\mu\text{G}$  literature. Compared to MOSFETs, thyristors operate at

a high voltage and current, but lower switching frequency. From a market survey, very few SiC thyristors are available to purchase. However, there are thyristors in the 6.5 kV range, which can pass up to 80 A of current, putting them in the 520 kW range, more than doubling the max SiC MOSFET unit power range.

Other SiC transistors are also available, such as JFET, which is a voltage controlled device (they commonly exist with the “ON” characteristic, which can be unfavourable, but techniques exist to make them normally “off”) and the BJT, which is a current controlled device. As these devices are not often discussed in relation to  $\mu$ G power systems, their characteristics will not be discussed further.

SiC IGBTs are discussed in the research literature, but no commercially available units were found at the time of writing [131].

### 3.2. Gallium Nitride

While the “either/or” mentality has often been applied to the subject of SiC and GaN, it is clear that each technology aims to operate in a different voltage range (with some overlap), and both have a place in future power electronic systems. SiC appears to dominate in high voltage, while the fast switching speeds of GaN has advantages, such as the ability to reduce the physical size of devices [132]. Another advantage of GaN is its ability to operate at high temperatures, reducing the need for bulky heat sinks, further reducing the physical size of its applications [133].

One of the major challenges that has faced GaN switches has been the creation of “normally-off” devices, crucial for power electronics [17]. This problem has been addressed through advanced manufacturing processes, with cascode transistors ((Si/GaN hybrid)), metal insulator semiconductor high-electron mobility transistor (gate recessing plus gate dielectric isolation techniques), p-GaN (p-GaN layer),  $F^-$  ion (ion implantation by plasma) [134].

Characteristics of commercially available GaN MOSFETs, as discussed in [135–142], are summarised below.

MOSFETs are commonly found in the 600 V to 650 V range, but can reach up to 1200 V [142]. Their current capacities in the 650 V range reach up to 60 A, while at the higher voltages of 900 V to 1200 V, they reach the 30 A range. This sits GaN comfortably in the 30 kW to 40 kW range of power application. A common  $R_{DS(ON)}$  for GaN is in the range of approximately 1 m $\Omega$  up to 560 m $\Omega$ , while the rise and fall time begin from less than 10 ns and in the tens of ns (generally less than 40 ns), respectively. GaN MOSFETs are capable of switching at very high speeds in the MHz range. This means that, compared to SiC, GaNs operate at a slightly lower voltage and power range, on average, and have a lower  $R_{DS(ON)}$  and rise/fall times in this voltage/power range.

While Schottky diodes are discussed and demonstrated in the academic literature, no commercially available diodes could be located. Schottky diodes display promising properties for power electronic systems to increase efficiency and switching speeds.

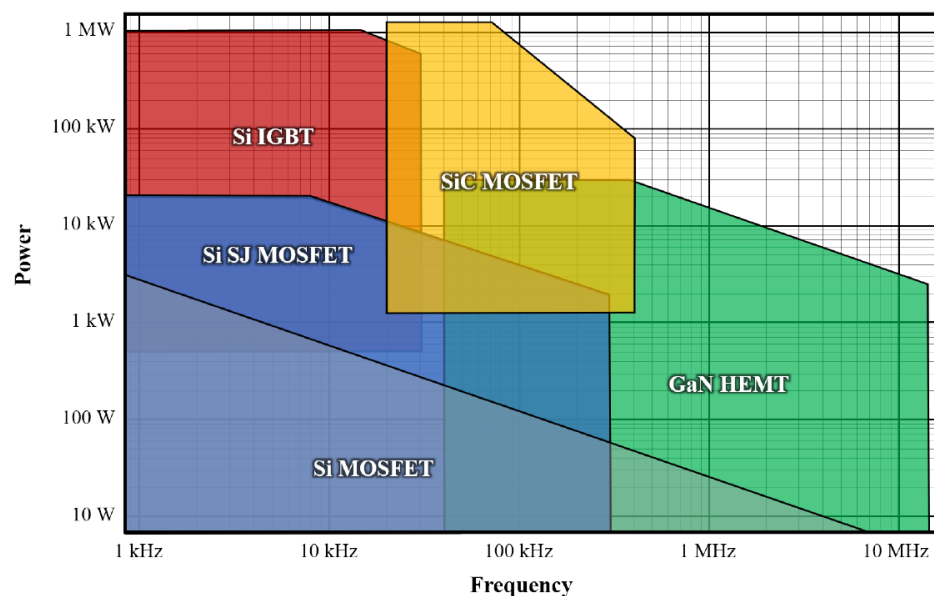
## 4. Wide-Bandgap Technologies in Microgrids

While many advantages are quoted for WBG materials, initial cost is still currently a barrier. For example, SiC requires specialised processing during fabrication, so, additional cost when compared to standard silicon is inherent in the manufacturing process. The manufacturing of GaN has the potential to be competitive with standard silicon devices as the economies of scale increase. Moreover, GaN can be grown on silicon substrates (except in the case of GaN on GaN or GaN on SiC), allowing manufacturers to leverage existing fabrication and tools [143]. Manufacturers are also working to increase wafer size, which will cut capital outlays and unit cost simultaneously.

When discussing the cost of WBG materials in relation to  $\mu$ Gs, the discussion must extend past component-level cost and look at the system level. The higher switching frequencies and improved thermal characteristics that WBG materials deliver allow for reduced passive component and cooling system costs, thus bringing down the overall system cost [8].

However, as the capital cost is currently higher than silicon, the question stands, where is it advantageous to use WBG materials in microgrids?

Figure 5 shows a comparison of the operating ranges for silicon-based IGBT and MOSFET switches, SiC, and GaN. It can be seen that silicon IGBTs operate at the lowest frequency but the highest power range. Silicon MOSFETs operate at lower power than IGBTs, but higher switching frequency. GaN operates at a similar power range to silicon MOSFETs, but at a higher switching frequency, while SiC operates at an order of magnitude higher power than silicon MOSFETs, and can exceed the switching frequency of both silicon IGBTs and MOSFETs.



**Figure 5.** Power vs. switching frequency of Si, SiC, and GaN [115].

While the high switching frequency implies a smaller physical size of passive components, one interesting point to keep in mind is which “figure of merit” is important to judge switches by in  $\mu$ G applications [144]. Certainly, for applications such as shipboards and aerospace, which fall into the wider category of  $\mu$ Gs, physical size is of the utmost importance. However, is this of benefit to the more traditional community/household  $\mu$ G systems? Evidence in the literature also points to the fact that along with the reduction in passive component size, there is also an increase in efficiency, which is advantageous in any application [144–149].

In Section 2.3.2, commonly presented  $\mu$ G voltage and power magnitudes are discussed. If these are cross-referenced with Figure 5, GaN is a candidate to replace Si MOSFETs in “short range” voltages (12 V, 24 V and 48 V) which operate in power levels under 1 kW, through to  $120V_{RMS}$  to  $230V_{RMS}$ , that operate at power levels less than 6 kW. The typical applications for these structures are small-scale DC  $\mu$ G (also known as nanogrids) and systems operating at conventional AC household voltages. Power electronics typically utilised in systems such as these include DC-to-DC converters (buck, boost, buck-boost, flyback, LLC converter), AC-to-DC rectifier circuits (which may have PFC), and DC-to-AC inverters (typically H bridge or potentially flyback microinverters).

There are power electronic converter examples in the literature, which explore comparisons between GaN and Si and the benefits this new technology offers.

In the case of DC-to-DC conversion, ref. [150] presents a GaN 2.5 kW LLC converter (DC to DC) with 48 V output and 270–330 V input, which can be used in applications such as electric vehicle battery chargers and renewable energy systems. System parameters are compared to standard Si, and an increase in efficiency across the frequencies tested (120 kHz to 170 kHz) is observed, with higher frequencies displaying an increase of approximately 1.2% in efficiency. Moreover, the GaN converter operates at high frequency, and in turn high power density in a wide range of applications. There are a number of instances recorded in the literature, where resonant converters increase system efficiency. For example, in ref. [151], a 300 W LLC resonant converter with an input voltage of 400 V DC and an output 12 V DC boasts a 1% increase in efficiency. In [152], a resonant converter with an input voltage of 48 V, an output voltage of 12 V, and an output current of 26 A is analysed. It shows an increase in efficiency of 1% when comparing GaN to Si.

It is not only resonant DC-to-DC converters that benefit from GaN characteristics. A 400 W buck-boost “ZETA” DC-to-DC converter topology is presented in [153], which converts 38–40 V to 400 V. When comparing GaN to Si, at 100 kHz switching frequency, this research observes as much as a 1.92% increase in efficiency due to the superior switching characteristics of GaN.

Presented in [154] is a 500 W bidirectional buck-boost DC-to-DC converter, appropriate for charging/discharging energy storage elements. The bus voltage is 400 V while the battery voltage is 40–96 V. A thorough analysis of losses in GaN and Si variants is undertaken, with the GaN converter increasing efficiency by as much as 3.8%. It is observed that this benefit is due to the GaN’s smaller on-state resistance and shorter switching times, and it is concluded that the decrease in passive component size could reasonably offset the additional cost of the GaN switches. In [155], a 1000 W interleaved boost DC-to-DC converter with an input voltage of 200 V and an output voltage of 400 V is analysed. The GaN device exhibits improved switching and conduction performance when compared to Si, which equates to a converter efficiency increase of approximately 2%.

The conversion of AC to DC is prevalent in applications such as data centres, interfacing AC and DC buses, interacting with the grid (for DC  $\mu$ Gs), and interfacing DC loads to AC  $\mu$ Gs. In [156], a GaN totem-pole bridgeless PFC is presented. A major benefit to GaN technologies in this application is the elimination of reverse recovery, creating a system with ultra-high efficiency and high power density. The soft-switching, 3.2 kW converter achieves an efficiency above 99% and 130 W/inch<sup>3</sup> power density. A variation of the totem-Pole PFC rectifier is discussed in [157], utilising a flying capacitor. A 3 kW four-level flying capacitor multilevel totem-pole PFC with 200V GaN devices is presented. The use of GaN switches has reduced switching voltage, reduced voltage stress on the inductor, and increased equivalent ripple frequency of the inductor. The converter achieves a power density of 125 W/inch<sup>3</sup> and peak efficiency of 99%.

In DC-to-AC conversion, ref. [158] presents an analysis of a GaN-based single-phase transformer-less PV grid tied inverter. The design investigates a 5 kW system, where the conversion from 400 V DC to 120 V AC is undertaken. The research concludes that the system’s efficiency can be improved by more than 3% when comparing GaN to Si. The reduced losses also have the benefit of decreasing the required heat sink volume by 30%, which in turn reduces the system volume. The research also shows that the switching frequency can be increased by a factor of 10 when compared to Si, reducing passive component size. Another inverter topology (T-Type Inverter) is analysed in [159], where a comparison between GaN and Si shows a 1.4% increase in efficiency and also that the heat sink volume of the converter can be reduced by 2.5 times. A neutral-point-

clamped multilevel inverter is explored in [160], where a five-level inverter at 20 kHz GaN is compared to Si driving a 5.5 kW induction motor. The GaN device demonstrates a 2.8% increase in efficiency, as well as a volume and weight reduction of approximately 70%.

Controlled switches tend to dominate these applications, putting GaN MOSFETs front and centre, but diodes would also play a major role, where GaN Schottky diodes would feature. As mentioned above, this will increase the power density of the conversion technologies, but more importantly, potential efficiency gains.

It is unlikely, that these “short range” voltages will feature any significant power quality measures, except for perhaps advanced control in DC-to-DC conversion, and DC to AC, where the PCC may participate in localised grid stability. Particularly in DC and hybrid  $\mu$ Gs, GaN may also feature in protection systems (SSCB, ZSCB and HBCB), taking advantage of the low conduction losses, ability to operate at increased temperatures, and high-frequency switching.

Voltages such as 350 V to 450 V, 600 V to 900 V, and 1000 V to 3000 V are in the operating range of SiC switches. This typically covers larger power structures such as community-level  $\mu$ Gs and commercial and industrial applications, where DC, AC, and hybrid distribution structures can be employed. All conversion types may be applicable in high-voltage/power  $\mu$ Gs (AC to DC, DC to DC, DC to AC, and also AC to AC, including solid-state transformers), meaning all power electronic converter types mentioned in Section 2.6 can fall into the SiC domain. In [161], an example of a 15 kW SiC VIENNA AC-to-DC converter is presented and compared to Si. The grid voltage of 400 V is converted to 700 V DC, and the comparison sees as much as a threefold reduction in losses when comparing the SiC to Si. The research does however conclude that the Si is a more cost-effective solution in this scenario.

Papers [162–165] analyse various DC-to-DC converter topologies to compare the performance of SiC and Si, and explore the gains offered. Bidirectional DC to DC can be utilised in charging/discharging storage solutions in  $\mu$ Gs. In [162,163], a 20 kW bidirectional DC-to-DC converter with the low side voltage of 300 V and high side voltage of 600 V is analysed. This converter shows an efficiency increase of approximately 1.2% when Si IGBTs are replaced with SiC MOSFETs. The research presented in [164] explores a 3 kW isolated bidirectional DC to DC with the input voltage of 260 V to 300 V and output voltage of 280 V. This converter observes a 2.6% increase in efficiency when upgrading Si to SiC. A 750 V, 100 kW DC-to-DC bidirectional DAB converter is presented in [165]. When comparing Si to SiC, the converter sees a 1% increase in efficiency. A 1 MW DC-to-DC converter with an input voltage of 11 kV and an output voltage of 800 V is considered in [166]. Two topologies compare the losses between Si and SiC, a DAB converter, and series resonant converter (SRC). The DAB converter sees an increase in efficiency (when Si is replaced with SiC) of 9.9%, while the SRC converter has an increase of 12.24%.

DC to AC is also a common application for SiC in the modern  $\mu$ G. Examples in the literature show the benefits of SiC over Si. The research performed in [167] compares a 20 kW three-phase six-switch two-level inverter with a DC link voltage of 800 V. At a switching frequency of 50 kHz, the SiC inverter increases efficiency by approximately 1.5% for the rated power output, and as the switching frequency is increased, the efficiency deficit also increases (to approximately 3% at 125 kHz). In [168], a hybrid three-level active neutral-point-clamped (3L-ANPC) inverter prototype for PV systems is demonstrated at 2 kW, with the input voltage of 800 V and output voltage of 220 V at 50 Hz. A comparison is made between Si IGBTs and SiC MOSFETs where it is found that the SiC is approximately 1% more efficient than the Si equivalent. An 11 kW single-phase inverter prototype with a DC bus voltage of 600 V and 380 V AC output voltage has been built in [169], to evaluate

and compare the performance of a SiC MOSFET and Si IGBT. In this application, the SiC implementation outperforms the Si; at 40 kHz, the increase in efficiency is over 2%.

Not as commonly discussed as other conversion types, AC-to-AC applications are presented in the literature. In [170], solid-state 20 kVA AC-to-AC transformer application is analysed. The research shows that not only does the SiC MOSFET have a higher frequency switching capability (7 to 10 times higher), the losses in the Si-based IGBT are also higher than that in the SiC MOSFET. In [171], a 1.5 MW wind turbine application is researched, and the efficiency at various wind speeds is analysed. It shows, for all wind speeds, SiC is more efficient than Si, with the highest difference at lower wind speeds, where SiC is approximately 5.5% more efficient than Si. Further analysis is performed at various switching frequencies (between 1 kHz and 50 kHz), where the SiC-based converter's efficiency drops by 1.1% per 5 kHz, while the Si's efficiency drops at the much higher rate of 4.9% per 5 kHz.

While applications presented show an increase in efficiency in each case, with SiC having an inherently higher cost associated with the technology, analysis may be required as to whether the gains in efficiency and/or power density outweighs the increased capital cost. This is particularly pertinent in applications where a large number of switches are required (MLI, traditional matrix converters, perhaps even DAB converters).

Due to the increase in complexity of a larger power structure, it is expected that high-power and voltage-level applications will require power quality mitigation circuitry. This may include solutions such as DVR, STATCOM, UPQC, UPFC, UPLC, SVR, and a voltage balancer. In [172], an all-SiC 30 kVA DVR is presented and shows a significant performance improvement when compared to other state-of-the-art topologies. A loss analysis is performed between Si IGBTs and SiC MOSFETs, with the latter showing an efficiency improvement for each operating condition. At higher operating powers (30 kW), the efficiency gain is not overly pronounced, at less than a half percent, while a greater than 10% difference in efficiency is seen at lower operating power (approximately 6 kW and below). In [173], a three-level neutral-point-clamped voltage-source converter is studied for STATCOM operation. A 100 kVA unit compares the efficiency of both SiC MOSFETs and IGBTs with Si IGBTs to find, operating in STATCOM mode, the SiC units are more efficient than the Si units. The results show the MOSFETs having the highest efficiency, improving on the Si by approximately 5% at 10 kHz, while the SiC MOSFETs and IGBTs have a similar efficiency. An active power filter is discussed in [174], where the authors show that SiC has the capability of covering significantly higher harmonic orders when compared to Si (up to 19th-order harmonic currents).

The increased switching speeds and thermal features of SiC also makes it particularly beneficial in protection systems which are crucial for high-voltage/power applications, particularly in DC and hybrid systems where arcing is likely to occur in a breaker during fault conditions. In [175] a bidirectional solid-state circuit breaker is presented utilising a normally-on SiC JFET where turn-off tests were run over a load range from 10 kW to 36 kW (600 V, 60 A). It showed that a turn-off time of approximately 10  $\mu$ S can be achieved with this implementation. A 100 A, 850 V, solid-state DC circuit breaker with SiC MOSFETs, SiC Schottky diodes, and SiC avalanche breakdown diodes is presented in [176]. The system can continuously conduct up to 100 A with 25 °C air cooling and has a footprint of only 32 square-centimeter. In [177], a solid-state circuit breaker operating at 1200 V DC with the capability of interrupting 75 A is presented. The SiC-based system has an ultrashort response time of 1.5  $\mu$ S and is reliable during on-state operation.

Of course, when any relatively new technology is introduced, there will inevitably be unforeseen difficulties, and WBG power switches are no exception. In [178] a number of failures in SiC operation are presented. Gate threshold voltage degradation is discussed,

which occurs when prolonged high gate voltage is applied, leading to a change in the MOSFET's threshold voltage. The MOSFET's intrinsic body diode is also a notable point of failure, with high  $\frac{dV}{dt}$  leading to avalanche failure. The forward voltage drop of the body diode has also been seen to increase as a result of defects in the SiC basal plane dislocations. Degradation in gate leakage current is also documented in the literature. Switches should be capable of handling pulse currents, a brief period where the current can exceed the switch's nominal rated capacity. In SiC MOSFETs, a short circuit event can cause high leakage currents to flow from the gate to the source. It has been shown that irreversible damage to SiC MOSFETs can be caused during short circuit stresses. Driving inductive devices can cause high voltage spikes, which in turn can lead to critical field breakdown. In [179], a review of GaN dynamic effects and reliability is presented. In GaN devices, threshold voltage shifts can occur due to trapped charge located directly under the gate finger. The result is a change in the device's threshold voltage. Another point of discussion is on-resistance increase, which can occur due to further charge trapped in the gate-source and gate-drain access regions. This is an increase in the resistance of the current path (between the drain and source), leading to higher conduction losses. It should be noted that in GaN on silicon devices, the problem was solved. Further, oxidation of the gate finger surface can be caused by temperature and electric field, which in turn can create "pits", leading to gate leakage increase. High gate-drain electric field can cause a time-dependent degradation of a transistor submitted to reverse stress and the gate current may increase during operation. The time-dependent degradation may also occur under forward bias (particularly if a normally-off p-gate structure is used).

## 5. Conclusions

Microgrids are seen to be a mainstay in future power structures, designed to see the integration of distributed generation and advanced control techniques to not only benefit consumers and the power grid, but also the environment. The enabling technology, to enhance system stability, integration, management, protection and control, is power electronics. While Si has enabled much of the progress to date, in the pursuit of efficiency and power density, WBG materials are signaled as the next major progression.

This paper has outlined power structures and power electronic applications where WBG may, and indeed do, feature in modern/future microgrids. It discusses commercially available WBG devices, specifically SiC and GaN, and outlines their operating regions within various microgrid topologies. Indeed, SiC and GaN are still maturing, but it is clear that both WBG materials will have applications in small-scale, and larger-scale microgrids.

GaN MOSFETs and diodes have the potential to feature in the interfacing of small-scale generators and loads to DC, AC, and hybrid microgrid buses via power electronic converters. GaN can excel in short range voltages and standard grid distribution voltages, with power ranges up to the tens of kiloWatts, with increased switching frequency, low conduction losses, and high operating temperatures, allowing for high efficiencies and power density.

SiC can operate at higher voltage and power ranges, with the same WBG benefits offered by GaN. This makes SiC ideal for operating in community/commercial/industrial-scale microgrids, with power levels in the hundreds of kiloWatts to low megaWatts.

WBG research is extremely dynamic, with many commercial applications well behind where the research currently sits. This means, heading into the future, the range of WBG applications will only increase, helping to improve microgrids in the future.

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## Abbreviations

The following abbreviations are used in this manuscript:

|           |                                                               |
|-----------|---------------------------------------------------------------|
| APF       | Active power filter                                           |
| AC        | Alternating current                                           |
| BJT       | Bipolar junction transistors                                  |
| CNC       | Computer numerical control                                    |
| CLR       | Current limiting reactor                                      |
| DC        | Direct current                                                |
| D-FACTS   | Distribution flexible alternating current transmission system |
| D-STATCOM | Distribution static synchronous compensator                   |
| DAB       | Dual-active-bridge                                            |
| DAHB      | Dual-active-half-bridge                                       |
| DVR       | Dynamic Voltage Restorer                                      |
| EV        | Electric vehicle                                              |
| eV        | Electron volts                                                |
| FACTS     | Flexible alternating current transmission System              |
| FCL       | Fault current limiter                                         |
| GaN       | Gallium nitride                                               |
| HBCB      | Hybrid circuit breakers                                       |
| IEC       | International electrotechnical commission                     |
| IEEE      | Institute of Electrical and Electronics Engineers             |
| IGBT      | Insulated-gate bipolar transistor                             |
| JFET      | Junction field effect transistors                             |
| $\mu$ G   | Microgrid                                                     |
| MOSFET    | Metal oxide field effect transistor                           |
| MOV       | Metal oxide varistor                                          |
| MLI       | Multilevel inverter                                           |
| OCR       | Over current relay                                            |
| OF        | Over frequency                                                |
| OV        | Over voltage                                                  |
| PV        | Photovoltaic                                                  |
| PCC       | Point of common coupling                                      |
| PFC       | Power factor correction                                       |
| RCB       | Residual circuit breaker                                      |
| RMS       | Root mean squared                                             |
| SVR       | Series Voltage Regulator                                      |
| SiC       | Silicon carbide                                               |
| SCR       | Silicon-Controlled Rectifier                                  |
| SEPIC     | Single-ended primary inductor converter                       |
| SSCB      | Solid-state circuit breakers                                  |
| SST       | Solid state transformer                                       |
| STATCOM   | Static synchronous compensator                                |
| SMC       | Sparse matrix converter                                       |
| SVC       | Static var compensators                                       |
| TCR       | Thyristor-controlled reactor                                  |
| TSC       | Thyristor-switched capacitor                                  |

|      |                                         |
|------|-----------------------------------------|
| USMC | Ultra sparse matrix converter           |
| UF   | Under frequency                         |
| UV   | Under voltage                           |
| UPFC | Unified Power Flow Controller           |
| UPQC | Unified power quality conditioner       |
| UPLC | Universal active power line conditioner |
| VSMC | Very sparse matrix converter            |
| VSC  | Voltage-source converters               |
| WBG  | Wide bandgap                            |
| ZSCB | Z-source circuit breaker                |

## References

1. Souza Junior, M.E.T.; Freitas, L.C.G. Power Electronics for Modern Sustainable Power Systems: Distributed Generation, Microgrids and Smart Grids—A Review. *Sustainability* **2022**, *14*, 3597. <https://doi.org/10.3390/su14063597>.
2. Thakar, S.; Vijay, A.S.; Doolla, S. System reconfiguration in microgrids. *Sustain. Energy Grids Netw.* **2019**, *17*, 100191. <https://doi.org/10.1016/j.segan.2019.100191>.
3. Shahbazi, M.; Khorsandi, A. Chapter 10—Power Electronic Converters in Microgrid Applications. In *Microgrid*; Mahmoud, M.S., Ed.; Butterworth-Heinemann: London, UK, 2017; pp. 281–309. <https://doi.org/10.1016/B978-0-08-101753-1.00010-3>.
4. Hussain, J.; Huang, Q.; Li, J.; Zhang, Z.; Hussain, F.; Ahmed, S.A.; Manzoor, K. Optimization of social welfare in P2P community microgrid with efficient decentralized energy management and communication-efficient power trading. *J. Energy Storage* **2024**, *81*, 110458. <https://doi.org/10.1016/j.est.2024.110458>.
5. Mbungu, N.T.; Ismail, A.A.; AlShabi, M.; Bansal, R.C.; Elnady, A.; Hamid, A.K. Control and estimation techniques applied to smart microgrids: A review. *Renew. Sustain. Energy Rev.* **2023**, *179*, 113251. <https://doi.org/10.1016/j.rser.2023.113251>.
6. Zekentes, K.; Veliadis, V.; Ryu, S.H.; Vasilevskiy, K.; Pavlidis, S.; Salemi, A.; Zhang, Y. SiC and GaN Power Devices. In *More-than-Moore Devices and Integration for Semiconductors*; Iacopi, F., Balestra, F., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 47–104. [https://doi.org/10.1007/978-3-031-21610-7\\_2](https://doi.org/10.1007/978-3-031-21610-7_2).
7. Rafin, S.M.S.H.; Ahmed, R.; Haque, M.A.; Hossain, M.K.; Haque, M.A.; Mohammed, O.A. Power Electronics Revolutionized: A Comprehensive Analysis of Emerging Wide and Ultrawide Bandgap Devices. *Micromachines* **2023**, *14*, 2045. <https://doi.org/10.3390/mi14112045>.
8. Mazumder, S.K.; Voss, L.F.; Dowling, K.M.; Conway, A.; Hall, D.; Kaplar, R.J.; Pickrell, G.W.; Flicker, J.; Binder, A.T.; Chowdhury, S.; et al. Overview of Wide/Ultrawide Bandgap Power Semiconductor Devices for Distributed Energy Resources. *IEEE J. Emerg. Sel. Top. Power Electron.* **2023**, *11*, 3957–3982. <https://doi.org/10.1109/JESTPE.2023.3277828>.
9. Liu, A.C.; Lai, Y.Y.; Chen, H.C.; Chiu, A.P.; Kuo, H.C. A Brief Overview of the Rapid Progress and Proposed Improvements in Gallium Nitride Epitaxy and Process for Third-Generation Semiconductors with Wide Bandgap. *Micromachines* **2023**, *14*, 764. <https://doi.org/10.3390/mi14040764>.
10. Qin, Y.; Albano, B.; Spencer, J.; Lundh, J.S.; Wang, B.; Buttay, C.; Tadjer, M.; DiMarino, C.; Zhang, Y. Thermal management and packaging of wide and ultra-wide bandgap power devices: A review and perspective. *J. Phys. D Appl. Phys.* **2023**, *56*, 093001. <https://doi.org/10.1088/1361-6463/acb4ff>.
11. Woo, K.; Bian, Z.; Noshin, M.; Martinez, R.P.; Malakoutian, M.; Shankar, B.; Chowdhury, S. From wide to ultrawide-bandgap semiconductors for high power and high frequency electronic devices. *J. Physics Mater.* **2024**, *7*, 022003. <https://doi.org/10.1088/2515-7639/ad218b>.
12. Wang, Y.; Ding, Y.; Yin, Y. Reliability of Wide Band Gap Power Electronic Semiconductor and Packaging: A Review. *Energies* **2022**, *15*, 6670. <https://doi.org/10.3390/en15186670>.
13. Zhang, B.; Wang, S. An Overview of Wide Bandgap Power Semiconductor Device Packaging Techniques for EMI Reduction. In *Proceedings of the 2018 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI)*; IEEE: New York, NY, USA, 2018; pp. 297–301. <https://doi.org/10.1109/EMCSI.2018.8495171>.
14. Das, A.; Kanjilal, M.R.; Mukherjee, M.; Santra, A. Review on Wide Band Gap Semiconductor. In *Proceedings of the 2022 IEEE International Conference of Electron Devices Society Kolkata Chapter (EDKCON)*; IEEE: New York, NY, USA, 2022; pp. 586–591. <https://doi.org/10.1109/EDKCON56221.2022.10032898>.
15. Tahir, M.; Hu, S.; He, X. Performance Improvement Strategies for Discrete Wide Bandgap Devices: A Systematic Review. *Front. Energy Res.* **2021**, *9*, 788689. <https://doi.org/10.3389/fenrg.2021.788689>.
16. Kumar, A.; Moradpour, M.; Losito, M.; Franke, W.T.; Ramasamy, S.; Baccoli, R.; Gatto, G. Wide Band Gap Devices and Their Application in Power Electronics. *Energies* **2022**, *15*, 9172. <https://doi.org/10.3390/en15239172>.

17. Iannaccone, G.; Sbrana, C.; Morelli, I.; Strangio, S. Power Electronics Based on Wide-Bandgap Semiconductors: Opportunities and Challenges. *IEEE Access* **2021**, *9*, 139446–139456. <https://doi.org/10.1109/ACCESS.2021.3118897>.
18. Garrido-Diez, D.; Baraia, I. Review of wide bandgap materials and their impact in new power devices. In *Proceedings of the 2017 IEEE International Workshop of Electronics, Control, Measurement, Signals and Their Application to Mechatronics (ECMSM)*; IEEE: New York, NY, USA, 2017; pp. 1–6. <https://doi.org/10.1109/ECMSM.2017.7945876>.
19. Rafin, S.M.S.H.; Ahmed, R.; Mohammed, O.A. Wide Band Gap Semiconductor Devices for Power Electronic Converters. In *Proceedings of the 2023 Fourth International Symposium on 3D Power Electronics Integration and Manufacturing (3D-PEIM)*; IEEE: New York, NY, USA, 2023; pp. 1–8. <https://doi.org/10.1109/3D-PEIM55914.2023.10052586>.
20. Parvez, M.; Pereira, A.T.; Ertugrul, N.; Weste, N.H.E.; Abbott, D.; Al-Sarawi, S.F. Wide Bandgap DC–DC Converter Topologies for Power Applications. *Proc. IEEE* **2021**, *109*, 1253–1275. <https://doi.org/10.1109/JPROC.2021.3072170>.
21. Van Do, T.; Trovão, J.P.F.; Li, K.; Boulon, L. Wide-Bandgap Power Semiconductors for Electric Vehicle Systems: Challenges and Trends. *IEEE Veh. Technol. Mag.* **2021**, *16*, 89–98. <https://doi.org/10.1109/MVT.2021.3112943>.
22. Gupta, G.; Ahmadi, E. (Ultra) wide-bandgap semiconductors for electric vehicles. *MRS Bull.* **2024**, *49*, 730–737.
23. Tang, Z.; Yang, Y.; Blaabjerg, F. Power electronics: The enabling technology for renewable energy integration. *CSEE J. Power Energy Syst.* **2022**, *8*, 39–52. <https://doi.org/10.17775/CSEEJPES.2021.02850>.
24. Ballestín-Fuertes, J.; Muñoz-Cruzado-Alba, J.; Sanz-Osorio, J.F.; Laporta-Puyal, E. Role of Wide Bandgap Materials in Power Electronics for Smart Grids Applications. *Electronics* **2021**, *10*, 677. <https://doi.org/10.3390/electronics10060677>.
25. Modu, B.; Abdullah, M.P.; Sanusi, M.A.; Hamza, M.F. DC-Based microgrid: Topologies, control schemes, and implementations. *Alex. Eng. J.* **2023**, *70*, 61–92.
26. IEC. *Electricity for the 21st Century*; International Electrotechnical Commission: Geneva, Switzerland, 2017.
27. Cabana-Jiménez, K.; Candelo-Becerra, J.E.; Sousa Santos, V. Comprehensive analysis of microgrids configurations and topologies. *Sustainability* **2022**, *14*, 1056.
28. Zhou, Y.; Ho, C.N.M. A review on microgrid architectures and control methods. In *Proceedings of the 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*; IEEE: New York, NY, USA, 2016; pp. 3149–3156.
29. Planas, E.; Andreu, J.; Gárate, J.I.; De Alegría, I.M.; Ibarra, E. AC and DC technology in microgrids: A review. *Renew. Sustain. Energy Rev.* **2015**, *43*, 726–749.
30. Justo, J.J.; Mwasilu, F.; Lee, J.; Jung, J.W. AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renew. Sustain. Energy Rev.* **2013**, *24*, 387–405.
31. Pires, V.F.; Pires, A.; Cordeiro, A. DC Microgrids: Benefits, Architectures, Perspectives and Challenges. *Energies* **2023**, *16*, 1217.
32. Shahgholian, G. A brief review on microgrids: Operation, applications, modeling, and control. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12885.
33. Abdelgawad, H.; Sood, V.K. A comprehensive review on microgrid architectures for distributed generation. In *Proceedings of the 2019 IEEE Electrical Power And Energy Conference (EPEC)*; IEEE: New York, NY, USA, 2019; pp. 1–8.
34. Unamuno, E.; Barrena, J.A. Hybrid ac/dc microgrids—Part I: Review and classification of topologies. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1251–1259. <https://doi.org/10.1016/j.rser.2015.07.194>.
35. Cagnano, A.; De Tuglie, E.; Mancarella, P. Microgrids: Overview and guidelines for practical implementations and operation. *Appl. Energy* **2020**, *258*, 114039. <https://doi.org/10.1016/j.apenergy.2019.114039>.
36. Guo, L.; Fu, X.; Zeng, J. Editorial: Power Management for AC/DC Hybrid Microgrid. *Front. Energy Res.* **2021**, *9*, 801894. <https://doi.org/10.3389/fenrg.2021.801894>.
37. Zhou, D.; Chen, S.; Wang, H.; Guan, M.; Zhou, L.; Wu, J.; Hu, Y. Autonomous Cooperative Control for Hybrid AC/DC Microgrids Considering Multi-Energy Complementarity. *Front. Energy Res.* **2021**, *9*, 692026. <https://doi.org/10.3389/fenrg.2021.692026>.
38. Azeem, O.; Ali, M.; Abbas, G.; Uzair, M.; Qahmash, A.; Algarni, A.; Hussain, M.R. A comprehensive review on integration challenges, optimization techniques and control strategies of hybrid AC/DC Microgrid. *Appl. Sci.* **2021**, *11*, 6242.
39. Yoldaş, Y.; Önen, A.; Muyeen, S.; Vasilakos, A.V.; İrfan Alan. Enhancing smart grid with microgrids: Challenges and opportunities. *Renew. Sustain. Energy Rev.* **2017**, *72*, 205–214. <https://doi.org/10.1016/j.rser.2017.01.064>.
40. Nejabatkhah, F.; Li, Y.W.; Tian, H. Power Quality Control of Smart Hybrid AC/DC Microgrids: An Overview. *IEEE Access* **2019**, *7*, 52295–52318. <https://doi.org/10.1109/ACCESS.2019.2912376>.
41. Uddin, M.; Mo, H.; Dong, D.; Elsayah, S.; Zhu, J.; Guerrero, J.M. Microgrids: A review, outstanding issues and future trends. *Energy Strategy Rev.* **2023**, *49*, 101127. <https://doi.org/10.1016/j.esr.2023.101127>.
42. Saha, D.; Bazmohammadi, N.; Vasquez, J.C.; Guerrero, J.M. Multiple Microgrids: A Review of Architectures and Operation and Control Strategies. *Energies* **2023**, *16*, 600. <https://doi.org/10.3390/en16020600>.
43. Adegbeyega, A.W.; Sepasi, S.; Howlader, H.O.R.; Griswold, B.; Matsuura, M.; Roose, L.R. DC Microgrid Deployments and Challenges: A Comprehensive Review of Academic and Corporate Implementations. *Energies* **2025**, *18*, 1064. <https://doi.org/10.3390/en18051064>.

44. Liberos, M.; González-Medina, R.; Patrao, I.; Torán, E.; Garcerá, G.; Figueres, E. A Control Stage for Parallel-Connected Interlinking Converters in Hybrid AC–DC Microgrids. *IEEE Access* **2023**, *11*, 61800–61812. <https://doi.org/10.1109/ACCESS.2023.3286569>.
45. Patnaik, B.; Mishra, M.; Bansal, R.C.; Jena, R.K. AC microgrid protection—A review: Current and future prospective. *Appl. Energy* **2020**, *271*, 115210. <https://doi.org/10.1016/j.apenergy.2020.115210>.
46. Pires, V.F.; Cordeiro, A.; Roncero-Clemente, C.; Rivera, S.; Dragičević, T. DC–DC Converters for Bipolar Microgrid Voltage Balancing: A Comprehensive Review of Architectures and Topologies. *IEEE J. Emerg. Sel. Top. Power Electron.* **2023**, *11*, 981–998. <https://doi.org/10.1109/JESTPE.2022.3208689>.
47. Carvalho, E.L.; Blinov, A.; Chub, A.; Emiliani, P.; de Carne, G.; Vinnikov, D. Grid Integration of DC Buildings: Standards, Requirements and Power Converter Topologies. *IEEE Open J. Power Electron.* **2022**, *3*, 798–823.
48. Anand, S.; Fernandes, B.G. Optimal voltage level for DC microgrids. In *Proceedings of the IECON 2010—36th Annual Conference on IEEE Industrial Electronics Society*; IEEE: New York, NY, USA, 2010; pp. 3034–3039. <https://doi.org/10.1109/IECON.2010.5674947>.
49. Burmester, D.; Rayudu, R.; Seah, W.; Akinyele, D. A review of nanogrid topologies and technologies. *Renew. Sustain. Energy Rev.* **2017**, *67*, 760–775.
50. Sabry, A.H.; Shallal, A.H.; Hameed, H.S.; Ker, P.J. Compatibility of household appliances with DC microgrid for PV systems. *Heliyon* **2020**, *6*, 1–29.
51. Lidula, N.; Rajapakse, A. Microgrids research: A review of experimental microgrids and test systems. *Renew. Sustain. Energy Rev.* **2011**, *15*, 186–202.
52. Neyret, Y. DC microgrids: Principles and benefits. *DC Syst. White Pap.* **2021**, *6*, e05699.
53. Rebollal, D.; Carpintero-Rentería, M.; Santos-Martín, D.; Chinchilla, M. Microgrid and Distributed Energy Resources Standards and Guidelines Review: Grid Connection and Operation Technical Requirements. *Energies* **2021**, *14*, 523. <https://doi.org/10.3390/en14030523>.
54. Iskender, I.; Genc, N. Power Electronic Converters in DC Microgrid. In *Microgrid Architectures, Control and Protection Methods*; Mahdavi Tabatabaei, N., Kabalci, E., Bizon, N., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 115–137. [https://doi.org/10.1007/978-3-030-23723-3\\_6](https://doi.org/10.1007/978-3-030-23723-3_6).
55. Rajendran, G.; Vaithilingam, C.A.; Misron, N.; Naidu, K.; Ahmed, M.R. Voltage Oriented Controller Based Vienna Rectifier for Electric Vehicle Charging Stations. *IEEE Access* **2021**, *9*, 50798–50809. <https://doi.org/10.1109/ACCESS.2021.3068653>.
56. Dong, D.; Thacker, T.; Cvetkovic, I.; Burgos, R.; Boroyevich, D.; Wang, F.; Skutt, G. Modes of Operation and System-Level Control of Single-Phase Bidirectional PWM Converter for Microgrid Systems. *IEEE Trans. Smart Grid* **2012**, *3*, 93–104. <https://doi.org/10.1109/TSG.2011.2167352>.
57. Tofoli, F.L.; Pereira, D.d.C.; Josias de Paula, W.; Oliveira Junior, D.d.S. Survey on non-isolated high-voltage step-up dc–dc topologies based on the boost converter. *IET Power Electron.* **2015**, *8*, 2044–2057.
58. Ríos, S.J.; Pagano, D.J.; Lucas, K.E. Bidirectional Power Sharing for DC Microgrid Enabled by Dual Active Bridge DC–DC Converter. *Energies* **2021**, *14*, 404. <https://doi.org/10.3390/en14020404>.
59. Joarder, S.; Ghosh, A. Design and Implementation of Dual Active Bridge Converter for DC Microgrid application. In *Proceedings of the 2022 IEEE Delhi Section Conference (DELCON)*; IEEE: New York, NY, USA, 2022; pp. 1–6. <https://doi.org/10.1109/DELCON54057.2022.9753372>.
60. Haneda, R.; Akagi, H. Power-Loss Characterization and Reduction of the 750-V 100-KW 16-KHz Dual-Active-Bridge Converter With Buck and Boost Mode. *IEEE Trans. Ind. Appl.* **2022**, *58*, 541–553. <https://doi.org/10.1109/TIA.2021.3129728>.
61. Zhou, H.; Duong, T.; Sing, S.T.; Khambadkone, A.M. Interleaved bi-directional Dual Active Bridge DC–DC converter for interfacing ultracapacitor in micro-grid application. In *Proceedings of the 2010 IEEE International Symposium on Industrial Electronics*; IEEE: New York, NY, USA, 2010; pp. 2229–2234. <https://doi.org/10.1109/ISIE.2010.5636841>.
62. Kondrath, N. Bidirectional DC–DC converter topologies and control strategies for interfacing energy storage systems in microgrids: An overview. In *Proceedings of the 2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE)*; IEEE: New York, NY, USA, 2017; pp. 341–345. <https://doi.org/10.1109/SEGE.2017.8052822>.
63. Zeng, J.; Zhang, G.; Yu, S.S.; Zhang, B.; Zhang, Y. LLC resonant converter topologies and industrial applications—A review. *Chin. J. Electr. Eng.* **2020**, *6*, 73–84. <https://doi.org/10.23919/CJEE.2020.000021>.
64. Gao, D.Z.; Sun, K. 16—DC–AC inverters. In *Electric Renewable Energy Systems*; Rashid, M.H., Ed.; Academic Press: Boston, MA, USA, 2016; pp. 354–381. <https://doi.org/10.1016/B978-0-12-804448-3.00016-5>.
65. Balal, A.; Dinkhah, S.; Shahabi, F.; Herrera, M.; Chuang, Y.L. A review on multilevel inverter topologies. *Emerg. Sci. J.* **2022**, *6*, 185–200.
66. Luo, F.L.; Hong, Y. *Renewable Energy Systems: Advanced Conversion Technologies and Applications*; CRC Press: Boca Raton, FL, USA, 2017.
67. Miveh, M.R.; Rahmat, M.F.; Ghadimi, A.A.; Mustafa, M.W. Control techniques for three-phase four-leg voltage source inverters in autonomous microgrids: A review. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1592–1610. <https://doi.org/10.1016/j.rser.2015.10.079>.

68. Hasan, R.; Mekhilef, S.; Seyedmahmoudian, M.; Horan, B. Grid-connected isolated PV microinverters: A review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 1065–1080. <https://doi.org/10.1016/j.rser.2016.09.082>.
69. Gaiceanu, M.; Arama, I.N.; Ghenea, I. Power Electronic Converters in AC Microgrid. In *Microgrid Architectures, Control and Protection Methods*; Mahdavi Tabatabaei, N., Kabalci, E., Bizon, N., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 139–175. [https://doi.org/10.1007/978-3-030-23723-3\\_7](https://doi.org/10.1007/978-3-030-23723-3_7).
70. Kolar, J.W.; Schafmeister, F.; Round, S.D.; Ertl, H. Novel Three-Phase AC–AC Sparse Matrix Converters. *IEEE Trans. Power Electron.* **2007**, *22*, 1649–1661. <https://doi.org/10.1109/TPEL.2007.904178>.
71. Gontijo, G.; Soares, M.; Tricarico, T.; Dias, R.; Aredes, M.; Guerrero, J. Direct Matrix Converter Topologies with Model Predictive Current Control Applied as Power Interfaces in AC, DC, and Hybrid Microgrids in Islanded and Grid-Connected Modes. *Energies* **2019**, *12*, 3302. <https://doi.org/10.3390/en12173302>.
72. Abu-Siada, A.; Budiri, J.; Abdou, A.F. Solid state transformers topologies, controllers, and applications: State-of-the-art literature review. *Electronics* **2018**, *7*, 298.
73. Mishra, D.K.; Ghadi, M.J.; Li, L.; Hossain, M.J.; Zhang, J.; Ray, P.K.; Mohanty, A. A review on solid-state transformer: A breakthrough technology for future smart distribution grids. *Int. J. Electr. Power Energy Syst.* **2021**, *133*, 107255.
74. Hartono, B.; Budiyo, Y.; Setiabudy, R. Review of microgrid technology. In *Proceedings of the 2013 International Conference on QiR*; IEEE: New York, NY, USA, 2013; pp. 127–132.
75. Badal, F.R.; Das, P.; Sarker, S.K.; Das, S.K. A survey on control issues in renewable energy integration and microgrid. *Prot. Control Mod. Power Syst.* **2019**, *4*, 1–27.
76. Bharatee, A.; Ray, P.K.; Subudhi, B.; Ghosh, A. Power Management Strategies in a Hybrid Energy Storage System Integrated AC/DC Microgrid: A Review. *Energies* **2022**, *15*, 7176. <https://doi.org/10.3390/en15197176>.
77. Saeed, M.H.; Fangzong, W.; Kalwar, B.A.; Iqbal, S. A review on microgrids' challenges & perspectives. *IEEE Access* **2021**, *9*, 166502–166517.
78. Sfikas, E.; Katsigiannis, Y.; Georgilakis, P. Simultaneous capacity optimization of distributed generation and storage in medium voltage microgrids. *Int. J. Electr. Power Energy Syst.* **2015**, *67*, 101–113. <https://doi.org/10.1016/j.ijepes.2014.11.009>.
79. Kumar, K.P.; Saravanan, B.; Swarup, K.S. Day ahead scheduling of generation and storage sources in a microgrid using artificial fish swarm algorithm. In *Proceedings of the 2016 21st Century Energy Needs—Materials, Systems and Applications (ICTFCEN)*; IEEE: New York, NY, USA, 2016; pp. 1–6. <https://doi.org/10.1109/ICTFCEN.2016.8052753>.
80. Ustun, T.S.; Ozansoy, C.; Zayegh, A. Recent developments in microgrids and example cases around the world—A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4030–4041.
81. Naderi, M.; Bahramara, S.; Khayat, Y.; Bevrani, H. Optimal planning in a developing industrial microgrid with sensitive loads. *Energy Rep.* **2017**, *3*, 124–134. <https://doi.org/10.1016/j.egyr.2017.08.004>.
82. Cetinkaya, H.B.; Kucuk, S.; Unaldi, M.; Gokce, G.B. A case study of a successful industrial microgrid operation. In *Proceedings of the 2017 4th International Conference on Electrical and Electronic Engineering (ICEEE)*; IEEE: New York, NY, USA, 2017; pp. 95–98. <https://doi.org/10.1109/ICEEE2.2017.7935800>.
83. Mondal, A.; Renjit, A.A.; Illindala, M.S.; Eto, J.H. Operation and impact of energy storage system in an industrial microgrid. In *Proceedings of the 2015 IEEE Industry Applications Society Annual Meeting*; IEEE: New York, NY, USA, 2015; pp. 1–7. <https://doi.org/10.1109/IAS.2015.7356935>.
84. Haj-ahmed, M.A.; Illindala, M.S. Investigation of protection schemes for flexible distribution of Energy and Storage resources in an industrial microgrid. In *Proceedings of the 2014 IEEE/IAS 50th Industrial and Commercial Power Systems Technical Conference*; IEEE: New York, NY, USA, 2014; pp. 1–10. <https://doi.org/10.1109/ICPS.2014.6839177>.
85. Ansari, S.; Chandel, A.; Tariq, M. A Comprehensive Review on Power Converters Control and Control Strategies of AC/DC Microgrid. *IEEE Access* **2021**, *9*, 17998–18015. <https://doi.org/10.1109/ACCESS.2020.3020035>.
86. Vuyyuru, U.; Maiti, S.; Chakraborty, C.; Pal, B.C. A Series Voltage Regulator for the Radial DC Microgrid. *IEEE Trans. Sustain. Energy* **2019**, *10*, 127–136. <https://doi.org/10.1109/TSTE.2018.2828164>.
87. Afonso, J.L.; Tanta, M.; Pinto, J.G.O.; Monteiro, L.F.C.; Machado, L.; Sousa, T.J.C.; Monteiro, V. A Review on Power Electronics Technologies for Power Quality Improvement. *Energies* **2021**, *14*, 8585. <https://doi.org/10.3390/en14248585>.
88. Gayatri, M.; Parimi, A.; Pavan Kumar, A. A review of reactive power compensation techniques in microgrids. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1030–1036. <https://doi.org/10.1016/j.rser.2017.08.006>.
89. Alkahtani, A.A.; Alfalahi, S.T.Y.; Athamneh, A.A.; Al-Shetwi, A.Q.; Mansor, M.B.; Hannan, M.A.; Agelidis, V.G. Power Quality in Microgrids Including Supraharmonics: Issues, Standards, and Mitigations. *IEEE Access* **2020**, *8*, 127104–127122. <https://doi.org/10.1109/ACCESS.2020.3008042>.
90. Kandil, T.; Adel Ahmed, M. Control and Operation of Dynamic Voltage Restorer With Online Regulated DC-Link Capacitor in Microgrid System. *Can. J. Electr. Comput. Eng.* **2020**, *43*, 331–341. <https://doi.org/10.1109/CJECE.2020.3002855>.
91. Ma, C.T.; Gu, Z.H. Investigation on GaN HEMTs Based Three-Phase STATCOM with Hybrid Control Scheme. *Micromachines* **2021**, *12*, 464. <https://doi.org/10.3390/mi12040464>.

92. Duarte, S.N.; Barbosa, P.G.; Kabalcı, E. Chapter 8—STATCOM and DSTATCOM with modular multilevel converters. In *Multilevel Inverters*; Kabalcı, E., Ed.; Academic Press: Cambridge, MA, USA, 2021; pp. 209–248. <https://doi.org/10.1016/B978-0-323-90217-5.00008-3>.
93. Lee, T.L.; Hu, S.H.; Chan, Y.H. Design of D-STATCOM for voltage regulation in Microgrids. In *Proceedings of the 2010 IEEE Energy Conversion Congress and Exposition*; IEEE: New York, NY, USA, 2010; pp. 3456–3463. <https://doi.org/10.1109/ECCE.2010.5618339>.
94. Chakraborty, S.; Mukhopadhyay, S.; Biswas, S.K. Coordination of D-STATCOM & SVC for Dynamic VAR Compensation and Voltage Stabilization of an AC Grid Interconnected to a DC Microgrid. *IEEE Trans. Ind. Appl.* **2022**, *58*, 634–644. <https://doi.org/10.1109/TIA.2021.3123264>.
95. Arias Velásquez, R.M.; Mejía Lara, J.V. Harmonic failure in the filter of Static Var Compensator. *Eng. Fail. Anal.* **2020**, *107*, 104207. <https://doi.org/10.1016/j.engfailanal.2019.104207>.
96. Virmani, R.; Gaur, P.; Santosi, H.; Mittal, A.; Singh, B. Performance comparison of UPQC and Active Power Filters for a non-linear load. In *Proceedings of the 2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India*; IEEE: New York, NY, USA, 2010; pp. 1–8. <https://doi.org/10.1109/PEDES.2010.5712559>.
97. Hashempour, M.M.; Savaghebi, M.; Vasquez, J.C.; Guerrero, J.M. A Control Architecture to Coordinate Distributed Generators and Active Power Filters Coexisting in a Microgrid. *IEEE Trans. Smart Grid* **2016**, *7*, 2325–2336. <https://doi.org/10.1109/TSG.2015.2488980>.
98. Masoum, M. Chapter 11—Unified Power Quality Conditioner (UPQC). In *Power Quality in Power Systems and Electrical Machines*; Fuchs, E.F., Masoum, M.A., Eds.; Academic Press: Burlington, MA, USA, 2008; pp. 443–468. <https://doi.org/10.1016/B978-012369536-9.50012-7>.
99. Wang, S.; Jing, L.; Zhao, Y.; Wickramasinghe, H.R.; Wu, X.; Konstantinou, G. Operation of Unified Power Flow Controller as Virtual Synchronous Generator. *IEEE Access* **2020**, *8*, 162569–162580. <https://doi.org/10.1109/ACCESS.2020.3021388>.
100. Gandhar, S.; Ohri, J.; Singh, M. Improvement of voltage stability of renewable energy sources-based microgrid using ANFIS-tuned UPFC. In *Proceedings of the Advances in Energy and Built Environment: Select Proceedings of TRACE 2018*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 133–143.
101. Paul, P.J.; Raglend, I.J.; Prakash, T.R.D. Universal power line manager for micro grid. In *Proceedings of the 2011 International Conference on Recent Advancements in Electrical, Electronics and Control Engineering*; IEEE: New York, NY, USA, 2011; pp. 30–35. <https://doi.org/10.1109/ICONRAEeCE.2011.6129751>.
102. Chakraborty, S.; Simoes, M. Advanced Active Filtering in a Single Phase High Frequency AC Microgrid. In *Proceedings of the 2005 IEEE 36th Power Electronics Specialists Conference*; IEEE: New York, NY, USA, 2005; pp. 191–197. <https://doi.org/10.1109/PESC.2005.1581623>.
103. Aredes, M.; Heumann, K.; Watanabe, E. An universal active power line conditioner. *IEEE Trans. Power Deliv.* **1998**, *13*, 545–551. <https://doi.org/10.1109/61.660927>.
104. Chhipa, A.A.; Kumar, V. DC-Microgrid Voltage Regulation using Dual Active Bridge based SVR. In *Proceedings of the 2021 7th International Conference on Electrical Energy Systems (ICEES)*; IEEE: New York, NY, USA, 2021; pp. 490–495. <https://doi.org/10.1109/ICEES51510.2021.9383696>.
105. Sun, J.; Lin, W.; Hong, M.; Loparo, K.A. Voltage Regulation of DC-Microgrid with PV and Battery. *IEEE Trans. Smart Grid* **2020**, *11*, 4662–4675. <https://doi.org/10.1109/TSG.2020.3005415>.
106. Beheshtaein, S.; Cuzner, R.; Savaghebi, M.; Guerrero, J.M. Review on microgrids protection. *IET Gener. Transm. Distrib.* **2019**, *13*, 743–759.
107. Beheshtaein, S.; Savaghebi, M.; Guerrero, J.M.; Cuzner, R.; Vasquez, J.C. A secondary-control based fault current limiter for four-wire three phase inverter-interfaced DGs. In *Proceedings of the IECON 2017—43rd Annual Conference of the IEEE Industrial Electronics Society*; IEEE: New York, NY, USA, 2017; pp. 2363–2368. <https://doi.org/10.1109/IECON.2017.8216398>.
108. Lei, F.; Ruifeng, G.; Wanrong, Z.; Xiaoping, Y. Type and characteristic analysis of fault current limiter. In *Proceedings of the 2011 1st International Conference on Electric Power Equipment—Switching Technology*; IEEE: New York, NY, USA, 2011; pp. 356–361. <https://doi.org/10.1109/ICEPE-ST.2011.6123007>.
109. Beheshtaein, S.; Cuzner, R.M.; Forouzesh, M.; Savaghebi, M.; Guerrero, J.M. DC Microgrid Protection: A Comprehensive Review. *IEEE J. Emerg. Sel. Top. Power Electron.* **2019**, early access. <https://doi.org/10.1109/JESTPE.2019.2904588>.
110. Chandra, A.; Singh, G.K.; Pant, V. Protection techniques for DC microgrid—A review. *Electr. Power Syst. Res.* **2020**, *187*, 106439. <https://doi.org/10.1016/j.epsr.2020.106439>.
111. Pei, X.; Cwikowski, O.; Vilchis-Rodriguez, D.S.; Barnes, M.; Smith, A.C.; Shuttleworth, R. A review of technologies for MVDC circuit breakers. In *Proceedings of the IECON 2016—42nd Annual Conference of the IEEE Industrial Electronics Society*; IEEE: New York, NY, USA, 2016; pp. 3799–3805. <https://doi.org/10.1109/IECON.2016.7793492>.
112. Bader, S.J.; Lee, H.; Chaudhuri, R.; Huang, S.; Hickman, A.; Molnar, A.; Xing, H.G.; Jena, D.; Then, H.W.; Chowdhury, N.; et al. Prospects for Wide Bandgap and Ultrawide Bandgap CMOS Devices. *IEEE Trans. Electron Devices* **2020**, *67*, 4010–4020. <https://doi.org/10.1109/TED.2020.3010471>.

113. Di Paolo Emilio, M. Wide-Bandgap Materials. In *GaN and SiC Power Devices: From Fundamentals to Applied Design and Market Analysis*; Springer Nature: Cham, Switzerland, 2024; pp. 19–34. [https://doi.org/10.1007/978-3-031-50654-3\\_3](https://doi.org/10.1007/978-3-031-50654-3_3).
114. Chaudhary, O.S.; Denai, M.; Refaat, S.S.; Pissanidis, G. Technology and Applications of Wide Bandgap Semiconductor Materials: Current State and Future Trends. *Energies* **2023**, *16*, 6689. <https://doi.org/10.3390/en16186689>.
115. Buffolo, M.; Favero, D.; Marcuzzi, A.; De Santi, C.; Meneghesso, G.; Zanoni, E.; Meneghini, M. Review and Outlook on GaN and SiC Power Devices: Industrial State-of-the-Art, Applications, and Perspectives. *IEEE Trans. Electron Devices* **2024**, *71*, 1344–1355. <https://doi.org/10.1109/TED.2023.3346369>.
116. GeneSiC Semiconductor. Products. 2024. Available online: <https://navitassemi.com/genesic-mosfets-products/> (accessed on 24 February 2026).
117. Toshiba Electronic Devices & Storage Corporation. Products. 2024. Available online: <https://toshiba.semicon-storage.com/eu/semiconductor/product/sic-power-devices.html> (accessed on 13 February 2024).
118. ROHM Semiconductor. Products. 2024. Available online: <https://www.rohm.com/products/sic-power-devices/sic-mosfet#easyPartFinder> (accessed on 13 February 2024).
119. STMicroelectronics NV. Products. 2024. Available online: <https://www.st.com/en/sic-devices/sic-mosfets/products.html> (accessed on 13 February 2024).
120. Littelfuse. Products. 2024. Available online: <https://www.littelfuse.com/search-results.aspx?q=SiC%20MOSFETs&t=SeriesTab> (accessed on 13 February 2024).
121. WeEn Semiconductor. Products. 2024. Available online: <https://www.ween-semi.com/en/product/silicon/1338> (accessed on 13 February 2024).
122. Solitron Devices. Products. 2024. Available online: <https://solitrondevices.com/silicon-carbide-products/silicon-carbide-mosfets/> (accessed on 13 February 2024).
123. Wolfspeed. Products. 2024. Available online: <https://www.wolfspeed.com/products/power/sic-mosfets/> (accessed on 13 February 2024).
124. Bosch Semiconductor. Products. 2024. Available online: <https://www.bosch-semiconductors.com/products/sic-power-devices/> (accessed on 21 February 2026).
125. Semikron Danfoss. Products. 2024. Available online: <https://www.semikron-danfoss.com/products/product-classes/sic/sic-mosfet.html#view/table/items/20/order/id-in-a+desc/> (accessed on 13 February 2024).
126. Choi, H. *Overview of Silicon Carbide Power Devices*; Fairchild Semiconductor: San Jose, CA, USA, 2016.
127. GeneSiC Semiconductor. Products. 2024. Available online: <https://genesicsemi.com/sic-mosfet/G2R1000MT33J/G2R1000MT33J.pdf> (accessed on 16 February 2024).
128. Infineon. IMZ120R350M1H Datasheet. 2024. Available online: [https://www.infineon.com/dgdl/Infineon-IMZ120R350M1H-DataSheet-v02\\_00-EN.pdf?fileId=5546d46269e1c019016a92fd75376687](https://www.infineon.com/dgdl/Infineon-IMZ120R350M1H-DataSheet-v02_00-EN.pdf?fileId=5546d46269e1c019016a92fd75376687) (accessed on 15 February 2024).
129. GeneSiC Semiconductor. Products. 2024. Available online: <https://genesicsemi.com/sic-schottky-mps/> (accessed on 16 February 2024).
130. Toshiba Electronic Devices & Storage Corporation. SiC Schottky Barrier Diodes. 2024. Available online: [https://toshiba.semicon-storage.com/info/application\\_note\\_en\\_20190404\\_AKX00463.pdf?did=65325](https://toshiba.semicon-storage.com/info/application_note_en_20190404_AKX00463.pdf?did=65325) (accessed on 16 February 2024).
131. Han, L.; Liang, L.; Kang, Y.; Qiu, Y. A Review of SiC IGBT: Models, Fabrications, Characteristics, and Applications. *IEEE Trans. Power Electron.* **2021**, *36*, 2080–2093. <https://doi.org/10.1109/TPEL.2020.3005940>.
132. Castellazzi, A.; Gurbinar, E.; Wang, Z.; Suliman Hussein, A.; Garcia Fernandez, P. Impact of Wide-Bandgap Technology on Renewable Energy and Smart-Grid Power Conversion Applications Including Storage. *Energies* **2019**, *12*, 4462. <https://doi.org/10.3390/en12234462>.
133. Chowdhury, S. 6—GaN-on-GaN power device design and fabrication. In *Wide Bandgap Semiconductor Power Devices*; Baliga, B.J., Ed.; Woodhead Publishing Series in Electronic and Optical Materials; Woodhead Publishing: Sawston, UK, 2019; pp. 209–248. <https://doi.org/10.1016/B978-0-08-102306-8.00006-X>.
134. Rudan, M.; Brunetti, R.; Reggiani, S. (Eds.) *Springer Handbook of Semiconductor Devices*; Springer: Cham, Switzerland, 2022.
135. Infineon. Products. 2024. Available online: <https://www.infineon.com/cms/en/product/power/gan-hemt-gallium-nitride-transistor/> (accessed on 23 February 2024).
136. Renesas. Products. 2024. Available online: <https://www.renesas.com/us/en/products/space-harsh-environment/rad-hard-hermetic/rad-hard-power/rad-hard-gan-fets> (accessed on 23 February 2024).
137. Texas Instruments. Products. 2024. Available online: <https://www.ti.com/power-management/gallium-nitride/products.html> (accessed on 23 February 2024).
138. Gansystems. Products. 2024. Available online: <https://gansystems.com/gan-transistors/#top> (accessed on 23 February 2024).
139. Nexperia. Products. 2024. Available online: <https://www.nexperia.com/products/gan-fets#/p=1,s=0,f=c,rpp=,fs=0,sc=,so=,es=> (accessed on 23 February 2024).
140. EPC. Products. 2024. Available online: <https://epc-co.com/epc/products/gan-fets-and-ics> (accessed on 23 February 2024).

141. STMicroelectronics NV. Products. 2024. Available online: <https://www.st.com/en/power-management/mastergan11.html> (accessed on 23 February 2024).
142. Transphormusa. Products. 2024. Available online: <https://www.transphormusa.com/en/products/> (accessed on 23 February 2024).
143. Beheshti, M. Wide-bandgap semiconductors: Performance and benefits of GaN versus SiC. In *Proceedings of the Analog Design Journal*; Texas Instruments: Singapore, 2020; pp. 1–5.
144. Fuentes, C.D.; Müller, M.; Bernet, S.; Kouro, S. SiC-MOSFET or Si-IGBT: Comparison of Design and Key Characteristics of a 690 V Grid-Tied Industrial Two-Level Voltage Source Converter. *Energies* **2021**, *14*, 3054. <https://doi.org/10.3390/en14113054>.
145. Ngwashi, D.K.; Nkwankwa, Y.S. Investigation of the Use of Silicon Carbide Power Mosfets in Microgrids Battery Charging Systems. Available at SSRN 4484159. Available online: <https://ssrn.com/abstract=4484159> (accessed on 21 February 2026).
146. Loncarski, J.; Ricco, M.; Monteiro, V.; Monopoli, V.G. Efficiency Comparison of a DC-DC Interleaved Converter Based on SiC-MOSFET and Si-IGBT Devices for EV Chargers. In *Proceedings of the 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*; IEEE: New York, NY, USA, 2020; Volume 1, pp. 517–522. <https://doi.org/10.1109/CPE-POWERENG48600.2020.9161559>.
147. Trivedi, S.S.; Sant, A.V. Comparative analysis of dual active bridge dc–dc converter employing Si, SiC and GaN MOSFETs for G2V and V2G operation. *Energy Rep.* **2022**, *8*, 1011–1019. <https://doi.org/10.1016/j.egy.2022.08.100>.
148. Khoshzaman, S.; Hahn, I. A Performance Comparison of GaN FET and Silicon MOSFET. In *Proceedings of the 2021 22nd IEEE International Conference on Industrial Technology (ICIT)*; IEEE: New York, NY, USA, 2021; Volume 1, pp. 127–133. <https://doi.org/10.1109/ICIT46573.2021.9453693>.
149. Pullabhatla, S.K.; Bobba, P.B.; Yadlapalli, S. Comparison of GAN, SIC, SI Technology for High Frequency and High Efficiency Inverters. In *Proceedings of the E3S Web of Conferences*; EDP Sciences: Les-Ulis, France, 2020; Volume 184, p. 01012.
150. Mortazavizadeh, S.A.; Palazzo, S.; Amendola, A.; De Santis, E.; Di Ruzza, D.; Panariello, G.; Sanseverino, A.; Velardi, F.; Busatto, G. High Frequency, High Efficiency, and High Power Density GaN-Based LLC Resonant Converter: State-of-the-Art and Perspectives. *Appl. Sci.* **2021**, *11*, 11350. <https://doi.org/10.3390/app112311350>.
151. Zhang, W.; Wang, F.; Costinett, D.J.; Tolbert, L.M.; Blalock, B.J. Investigation of Gallium Nitride Devices in High-Frequency LLC Resonant Converters. *IEEE Trans. Power Electron.* **2017**, *32*, 571–583. <https://doi.org/10.1109/TPEL.2016.2528291>.
152. Reusch, D.; Strydom, J. Evaluation of Gallium Nitride Transistors in High Frequency Resonant and Soft-Switching DC–DC Converters. *IEEE Trans. Power Electron.* **2015**, *30*, 5151–5158. <https://doi.org/10.1109/TPEL.2014.2364799>.
153. Al-bayati, A.M.S.; Matin, M. A Highly Efficient GaN E-HEMT/SiC Schottky Diode Power Device Based DC–DC ZETA Converter. In *Proceedings of the 2018 IEEE Conference on Technologies for Sustainability (SusTech)*; IEEE: New York, NY, USA, 2018; pp. 1–5. <https://doi.org/10.1109/SusTech.2018.8671330>.
154. Alharbi, S.S.; Matin, M. Experimental evaluation of medium-voltage cascode gallium nitride (GaN) devices for bidirectional DC-DC converters. *CES Trans. Electr. Mach. Syst.* **2021**, *5*, 232–248. <https://doi.org/10.30941/CESTEMS.2021.000227>.
155. Alharbi, S.S.; Alharbi, S.S.; Matin, M. Effects of Gallium Nitride (GaN) Cascode FETs on the Efficiency of an Interleaved DC-DC Converter. In *Proceedings of the 2018 IEEE International Conference on Electro/Information Technology (EIT)*; IEEE: New York, NY, USA, 2018; pp. 0384–0389. <https://doi.org/10.1109/EIT.2018.8500116>.
156. Huang, Q.; Huang, A.Q. Review of GaN totem-pole bridgeless PFC. *CPSS Trans. Power Electron. Appl.* **2017**, *2*, 187–196. <https://doi.org/10.24295/CPSSSTPEA.2017.00018>.
157. Huang, Q.; Ma, Q.; Liu, P.; Huang, A.Q.; de Rooij, M. 3kW Four-Level Flying Capacitor Totem-Pole Bridgeless PFC Rectifier with 200V GaN Devices. In *Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE)*; IEEE: New York, NY, USA, 2019; pp. 81–88. <https://doi.org/10.1109/ECCE.2019.8913025>.
158. Alatawi, K.; Almasoudi, F.; Manandhar, M.; Matin, M. Comparative Analysis of Si- and GaN-Based Single-Phase Transformer-Less PV Grid-Tied Inverter. *Electronics* **2018**, *7*, 34. <https://doi.org/10.3390/electronics7030034>.
159. Gurpinar, E.; Castellazzi, A. Single-Phase T-Type Inverter Performance Benchmark Using Si IGBTs, SiC MOSFETs, and GaN HEMTs. *IEEE Trans. Power Electron.* **2016**, *31*, 7148–7160. <https://doi.org/10.1109/TPEL.2015.2506400>.
160. Mecke, R. Multilevel Inverter with New Wide-Bandgap SiC and GaN Power Switches. In *Proceedings of the 2021 IEEE 15th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*; IEEE: New York, NY, USA, 2021; pp. 1–6. <https://doi.org/10.1109/CPE-POWERENG50821.2021.9501170>.
161. Järvisalo, H.; Korhonen, J.; Silventoinen, P.; Korhonen, P. Techno-economical comparison between Si and SiC switches in a VIENNA rectifier. In *Proceedings of the 2021 IEEE 30th International Symposium on Industrial Electronics (ISIE)*; IEEE: New York, NY, USA, 2021; pp. 1–4. <https://doi.org/10.1109/ISIE45552.2021.9576406>.
162. Han, D.; Noppakunkajorn, J.; Sarlioglu, B. Comprehensive Efficiency, Weight, and Volume Comparison of SiC- and Si-Based Bidirectional DC–DC Converters for Hybrid Electric Vehicles. *IEEE Trans. Veh. Technol.* **2014**, *63*, 3001–3010. <https://doi.org/10.1109/TVT.2014.2323193>.

163. Han, D.; Noppakunkajorn, J.; Sarlioglu, B. Efficiency comparison of SiC and Si-based bidirectional DC-DC converters. In *Proceedings of the 2013 IEEE Transportation Electrification Conference and Expo (ITEC)*; IEEE: New York, NY, USA, 2013; pp. 1–7. <https://doi.org/10.1109/ITEC.2013.6574511>.
164. Zhao, B.; Song, Q.; Liu, W. Experimental Comparison of Isolated Bidirectional DC-DC Converters Based on All-Si and All-SiC Power Devices for Next-Generation Power Conversion Application. *IEEE Trans. Ind. Electron.* **2014**, *61*, 1389–1393. <https://doi.org/10.1109/TIE.2013.2258304>.
165. Akagi, H.; Kinouchi, S.; Miyazaki, Y. Bidirectional isolated dual-active-bridge (DAB) DC-DC converters using 1.2-kV 400-A SiC-MOSFET dual modules. *CPSS Trans. Power Electron. Appl.* **2016**, *1*, 33–40. <https://doi.org/10.24295/CPSSSTPEA.2016.00004>.
166. Moballegh, S.; Madhusoodhanan, S.; Bhattacharya, S. Evaluation of high voltage 15 kV SiC IGBT and 10 kV SiC MOSFET for ZVS and ZCS high power DC-DC converters. In *Proceedings of the 2014 International Power Electronics Conference (IPEC-Hiroshima 2014—ECCE ASIA)*; IEEE: New York, NY, USA, 2014; pp. 656–663. <https://doi.org/10.1109/IPEC.2014.6869657>.
167. Nitzsche, M.; Cheshire, C.; Fischer, M.; Ruthardt, J.; Roth-Stielow, J. Comprehensive Comparison of a SiC MOSFET and Si IGBT Based Inverter. In *Proceedings of the PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*; VDE-Verlag: Offenbach, Germany, 2019; pp. 1–7.
168. Zhang, L.; Lou, X.; Li, C.; Wu, F.; Gu, Y.; Chen, G.; Xu, D. Evaluation of Different Si/SiC Hybrid Three-Level Active NPC Inverters for High Power Density. *IEEE Trans. Power Electron.* **2020**, *35*, 8224–8236. <https://doi.org/10.1109/TPEL.2019.2962907>.
169. Wang, G.; Wang, F.; Magai, G.; Lei, Y.; Huang, A.; Das, M. Performance comparison of 1200 V 100 A SiC MOSFET and 1200 V 100 A silicon IGBT. In *Proceedings of the 2013 IEEE Energy Conversion Congress and Exposition*; IEEE: New York, NY, USA, 2013; pp. 3230–3234. <https://doi.org/10.1109/ECCE.2013.6647124>.
170. Wang, G.; Huang, X.; Wang, J.; Zhao, T.; Bhattacharya, S.; Huang, A.Q. Comparisons of 6.5 kV 25 A Si IGBT and 10-kV SiC MOSFET in Solid-State Transformer application. In *Proceedings of the 2010 IEEE Energy Conversion Congress and Exposition*; IEEE: New York, NY, USA, 2010; pp. 100–104. <https://doi.org/10.1109/ECCE.2010.5618069>.
171. Zhang, H.; Tolbert, L.M. Efficiency Impact of Silicon Carbide Power Electronics for Modern Wind Turbine Full Scale Frequency Converter. *IEEE Trans. Ind. Electron.* **2011**, *58*, 21–28. <https://doi.org/10.1109/TIE.2010.2048292>.
172. Ceccarelli, L.; Xu, X.; Tibola, G.; Duarte, J.L. Design and Analysis of a High-Efficiency All-SiC Dynamic Voltage Restorer for Wide-Range Sag/Swell Mitigation. In *Proceedings of the 2021 IEEE Energy Conversion Congress and Exposition (ECCE)*; IEEE: New York, NY, USA, 2021; pp. 3168–3175. <https://doi.org/10.1109/ECCE47101.2021.9595998>.
173. Madhusoodhanan, S.; Hatua, K.; Bhattacharya, S.; Leslie, S.; Ryu, S.H.; Das, M.; Agarwal, A.; Grider, D. Comparison study of 12kV n-type SiC IGBT with 10kV SiC MOSFET and 6.5kV Si IGBT based on 3L-NPC VSC applications. In *Proceedings of the 2012 IEEE Energy Conversion Congress and Exposition (ECCE)*; IEEE: New York, NY, USA, 2012; pp. 310–317. <https://doi.org/10.1109/ECCE.2012.6342807>.
174. Li, D.; Nie, C.; Huang, X.; Lin, M.; Wang, F.; Tolbert, L.M. Active Power Filter Capability of a 10 kV SiC MOSFET-Based Asynchronous Microgrid Power Conditioning System. In *Proceedings of the 2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*; IEEE: New York, NY, USA, 2023; pp. 137–143. <https://doi.org/10.1109/APEC43580.2023.10131265>.
175. Urciuoli, D.P.; Veliadis, V.; Ha, H.C.; Lubomirsky, V. Demonstration of a 600-V, 60-A, bidirectional silicon carbide solid-state circuit breaker. In *Proceedings of the 2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*; IEEE: New York, NY, USA, 2011; pp. 354–358. <https://doi.org/10.1109/APEC.2011.5744620>.
176. Urciuoli, D.P.; Ibitayo, D.; Koebke, G.; Ovrebo, G.; Green, R. A compact 100-A, 850-V, silicon carbide solid-state DC circuit breaker. In *Proceedings of the 2016 IEEE Energy Conversion Congress and Exposition (ECCE)*; IEEE: New York, NY, USA, 2016; pp. 1–5. <https://doi.org/10.1109/ECCE.2016.7854656>.
177. Ren, Y.; Yang, X.; Zhang, F.; Wang, F.; Tolbert, L.M.; Pei, Y. A Single Gate Driver Based Solid-State Circuit Breaker Using Series Connected SiC MOSFETs. *IEEE Trans. Power Electron.* **2019**, *34*, 2002–2006. <https://doi.org/10.1109/TPEL.2018.2861920>.
178. Ngwashi, D.K.; Phung, L.V. Recent review on failures in silicon carbide power MOSFETs. *Microelectron. Reliab.* **2021**, *123*, 114169. <https://doi.org/10.1016/j.microrel.2021.114169>.
179. De Santi, C.; Meneghini, M.; Meneghesso, G.; Zanoni, E. Review of dynamic effects and reliability of depletion and enhancement GaN HEMTs for power switching applications. *IET Power Electron.* **2018**, *11*, 668–674.

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