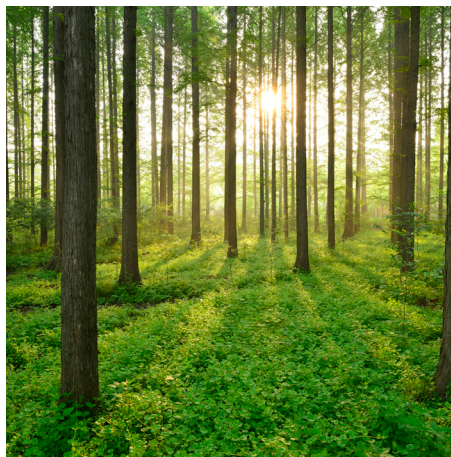


EXCHANGE STRATEGIES FOR POWER ELECTRONICS IN RECTIFIERS AND UPS SYSTEM FOR NPP

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GRID INTERACTION WITH
NUCLEAR POWER PLANT
OPERATIONS, GINO



Exchange Strategies for Power Electronics in Rectifiers and UPS System for NPP

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Foreword

This report forms the results of a project performed with the Energiforsk Energiforsk Grid Interaction with Nuclear power plant Operations (GINO) Program. The GINO Program aims to increase the knowledge of aspects of the interactions between the external grid and the Nordic nuclear power plants. Part of this is to investigate technical issues.

The reliability of auxiliary power systems in nuclear power plants is crucial for safety. These safety systems utilize power electronic components. When power electronics need to be replaced, the new equipment may not only have a different design, but also different technology and thus different electrical behavior. The aim of this study is to investigate the operational challenges involved in exchanging power electronics.

The results highlight the importance of adopting advanced technologies and predictive maintenance. Recommendations for the exchange phase include careful consideration of robustness, reliability, and compliance with modern safety standards as well as gradual implementation and enhanced monitoring to maintain system reliability during the transition phase.

The study was carried out by Yubo Song, Huai Wang, and Frede Blaabjerg, Aalborg University. The study was performed within the Energiforsk GINO Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, the Swedish Radiation Safety Authority and Svenska Kraftnät.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

This project focuses on replacing obsolete power electronics in nuclear power plant (NPP) auxiliary systems to enhance safety, reliability, and compliance with modern standards. It evaluates advanced power electronic components, particularly wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN), and analyzes their impact on system robustness, fault tolerance, and operational efficiency.

The findings highlight the technological shift driven by SiC and GaN semiconductors, which offer improved efficiency and thermal resilience but require new design considerations. Ensuring compliance with industry standards such as IEC 62855, IEC 63046, and IEC 61225 is crucial for safe operation in high-stress environments. However, replacing legacy components presents challenges due to differences in electrical behavior and fault tolerance, necessitating the integration of fault detection mechanisms and predictive maintenance strategies.

The study also examines DC/DC and DC/AC converters, redundancy strategies, and uninterruptible power supply (UPS) control techniques, alongside cooling methods such as air, liquid, and phase-change cooling. Practical implications include guidelines for selecting replacement components based on performance, reliability, and regulatory compliance, as well as the implementation of real-time condition monitoring to detect failures early. Modular and scalable designs with fault-tolerance strategies are recommended to improve long-term system stability.

Replacing legacy power electronics with modern, high-efficiency components is essential for maintaining NPP reliability and safety. A strategic approach is required to ensure seamless integration, regulatory compliance, and system resilience. The insights from this project provide valuable guidance for Nordic NPPs in adopting future-proof solutions.

Keywords:

Power electronics replacement, nuclear power plant reliability, wide-bandgap semiconductors, uninterruptible Power Supply (UPS), SiC and GaN semiconductors

Sammanfattning

Detta projekt fokuserar på att ersätta föråldrad kraftelektronik i hjälpsystem för kärnkraftverk (NPP) för att förbättra säkerhet, tillförlitlighet och efterlevnad av moderna standarder. Det utvärderar avancerade kraftelektroniska komponenter, särskilt bredbandshalvledare såsom kiselkarbid (SiC) och galliumnitrid (GaN), och analyserar deras inverkan på systemets robusthet, feltolerans och driftseffektivitet.

Resultaten belyser den teknologiska övergången som drivs av SiC- och GaN-halvledare, vilka erbjuder förbättrad verkningsgrad och termisk tålighet men kräver nya konstruktionsöverväganden. Efterlevnad av branschstandarder såsom IEC 62855, IEC 63046 och IEC 61225 är avgörande för säker drift i högbelastade miljöer. Dock innebär ersättning av äldre komponenter utmaningar på grund av skillnader i elektriskt beteende och feltolerans, vilket gör det nödvändigt att integrera felavkänningsmekanismer och prediktivt underhåll.

Studien undersöker även DC/DC- och DC/AC-omvandlare, redundansstrategier och kontrolltekniker för avbrottsfri kraftförsörjning (UPS), tillsammans med kylmetoder såsom luft-, vätske- och fasomvandlingskylning. Praktiska implikationer inkluderar riktlinjer för att välja ersättningskomponenter baserat på prestanda, tillförlitlighet och regulatorisk efterlevnad, samt implementering av realtidsövervakning för att tidigt upptäcka fel. Modulära och skalbara konstruktioner med feltoleransstrategier rekommenderas för att förbättra systemets långsiktiga stabilitet.

Att ersätta äldre kraftelektronik med moderna, högpresterande komponenter är avgörande för att upprätthålla NPP:s tillförlitlighet och säkerhet. En strategisk metod krävs för att säkerställa sömlös integration, regulatorisk efterlevnad och systemresiliens. Insikterna från detta projekt ger värdefulla riktlinjer för nordiska kärnkraftverk i deras övergång till framtidssäkra lösningar.

Nyckelord:

Utbyte av kraftelektronik, kärnkraftverkets tillförlitlighet, bredbandsgap-halvledare, avbrottsfri kraftförsörjning (UPS), SiC- och GaN-halvledare

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1 Introduction

1.1 BACKGROUND

The functionality and reliability of auxiliary power systems are essential and necessary for nuclear power plant safety. These safety systems utilize power electronic components for rectifiers, converters and inverters. In addition, power electronic components, used in excitation systems of nuclear power plant (NPP) main generator and emergency diesel generators, are of essential interest due to higher load level and harsh environment comparing to power electronic components in low voltage distribution systems. The equipment deterioration may bring a negative impact on the surrounding system. At a certain point developed degradation in the device may be a reason of future unexpected failures during severe transients.

Existing equipment can be maintained and repaired normally as long as the overall equipment condition is good, spare parts are available, and supplier keeps up their competence on the equipment. If any of these factors start deteriorating, problems emerge. If ageing causes frequent faults, spare parts are going out of stock or components are going out of production, it is motivated or necessary with a replacement to “state of the art” equipment. The issue is that typical power electronic devices available on the market today may differ a lot from what was originally installed. New equipment that will be installed in the NPPs not only may have a different design, but also a different technology and thus different electrical behavior. Moreover, from a long-term perspectives point of view, what kind of operational challenges are expected by utilizing advanced power electronics, e.g. modules with enhanced power density or new substrate technology, in NPP industry?

Therefore, the main objective of the project is to understand:

1. How to manage the replacement of legacy or obsolete power electronic solutions—including, but not limited to, thyristor-based systems, early-generation IGBT modules, and analog-controlled rectifiers—that may lack the fault tolerance, modularity, or monitoring capabilities required by modern standards. The goal is to ensure that new designs and packaging technologies meet current safety, robustness, and functional compliance requirements.
2. Design aspects impacting the robustness of the entire equipment i.e., how to evaluate transient impact on components taking the complete equipment/system design into account.
3. Future challenges to be expected with advanced power electronics.

1.2 PROJECT PROPOSAL

The project is planned to run by the experts at Aalborg University, department of AAU Energy with expertise in power electronics and its integration into energy systems including power electronic reliability, power system reliability, stability, and electromagnetic interference and compatibility (EMI/EMC). AAU has been

running various projects both in basic research and industrial projects covering emerging challenges with new power electronics technologies and their integration into energy systems. We are also active in various international and national standardization committees, e.g., IEC and Cigre especially for DC system.

1.3 SCOPE OF WORK

The project scope includes equipment choice and considerations about functionality vs robustness when exchanging equipment containing power electronic in a nuclear power plant safety system. The focus of the study will be on the converters, rectifiers feeding the DC buses, batteries and DC/DC converters inside the DC grid and UPS devices.

Initially a literature study and information compilation will be made based on at least the following sources:

- Requirement and standards for safety and reliable operation compilation for DC systems, including generator excitation bridges, and UPS protected environments at nuclear power plants (international as well as national standards)
- Literature study of
 - o Choice of technology solutions with regards to robustness.
 - o State-of-the-art solutions for power electronic especially for the voltage levels and loads, applied in auxiliary system and generator excitation circuits. Internal features, such as voltage ripple, overcurrent, harmonic distortion, and thermal load should be taken into consideration. An overview in terms of controllability (controllable, semi-controlled, uncontrolled), package choice (IGBT, IGCT, diode, GaN, SiC and others), maintenance, cooling and condition monitoring.
- Input on solutions from reputable manufacturers – according to our collaboration with them on different relevant projects.
- Interviews and interaction with the Nordic NPPs for input about experiences and requirements.

The following aspects will be analyzed in the project:

1. Examples of solutions and components that have expired in the market and reached “End of production” should be given together with examples of current solutions that can be/has been used to replace them.
2. Analyze what parameters are important to consider when evaluating new power electronics when the old one has expired from the market. Various types of rectifiers and DC/DC converters in the market shall be identified and described in terms of design, component content, control and resilience to external grid disturbances.

1.4 METHOD

1.4.1 Phase 1 – Setting the Picture

Literature studies and compilation of a relevant knowledge base have been performed. Information was gathered on the replacement of power converters with new technologies, innovative designs, and topologies that improve robustness and reliability using both active and passive methods (at design and control levels), particularly in relation to upstream disturbances and common cause failures.

Interviews were also conducted with representatives from Nordic nuclear power plants (NPPs), covering:

- Experiences of safety system equipment vulnerability to disturbances from the external grid.
- Insights and data related to equipment aging and failures, particularly for components involving power electronics.
- Current operational, maintenance, and monitoring strategies.

1.4.2 Phase 2 – Analysis and Validation

The insights from Phase 1 provided the basis for the analytical work in Phase 2. General aspects of the impact of upstream disturbances on modern converters, methods to enhance resilience and reliability, and the influence of failure mechanisms and common cause failures have been analyzed in the context of nuclear power applications. These analyses were scenario-based, with results validated using historical data from NPPs and documented disturbances from the literature.

The following specific questions are addressed:

- How can the power electronics design and components of today be compared to what was used in the past (e.g. 20 years ago) and how does it affect equipment robustness.
- Is the robustness of a component or converter/rectifier with regards to external and internal faults, just a design issue?
- How to quantify the isolating properties for both active and passive components of the equipment, i.e., if there is a disturbance upstream of the device, how can the likelihood of propagating downstream be minimized? Which design choices influence the isolating properties and to what degree?
- Is the risk of common cause failure affected by ageing and if so to what extent?

1.4.3 Phase 3 – Conclude and Compile Guideline Recommendations

The final phase of the project has focused on drawing conclusions and offering practical recommendations for replacing power electronics in rectifiers and UPS systems. These recommendations are based on the findings from analyses and condition monitoring strategies.

2 Requirements and Standards for Safety and Reliable Operation

2.1 STANDARDS

The safe and reliable operation of NPPs heavily relies on well-designed electrical power systems that comply with rigorous standards. The following subsections outline the key standards that govern the design, operation, and maintenance of electrical power systems in NPPs, ensuring they support critical safety functions and operational resilience.

2.1.1 IEC 62855:2016 - NPPs - Electrical power systems - Electrical power systems analysis

IEC 62855:2016 offers comprehensive electrotechnical engineering guidelines for the analysis of both AC and DC electrical power systems in NPPs. The primary objective of this standard is to demonstrate that the power sources and distribution systems are capable of supporting safe operation and maintaining the nuclear plant in a controlled shutdown state during anticipated operational occurrences, accidents, and design extension conditions. It underscores the critical role of electrical power systems in supporting nuclear safety functions, ensuring the stability of plant operations under various plant conditions [1].

Key applications of the standard include:

- It serves as a fundamental tool in verifying the design and adequacy of new nuclear power plants, ensuring that all system components meet safety and operational requirements.
- IEC 62855:2016 is used to assess major modifications or upgrades to existing electrical systems, ensuring continued compliance with safety standards.
- It helps in setting operational limits and constraints to guarantee ongoing safe operations.
- Through extensive analytical studies, this standard validates the robustness of electrical systems, including their margins to accommodate normal, abnormal, and degraded operational states.

IEC 62855 emphasizes that the system's ability to support safety functions during all plant conditions must be verified. This verification is accomplished through a combination of simulation tools (software or hardware), hand calculations, and physical tests. These analyses are necessary to confirm that the electrical power system can withstand minor disturbances and ensure that significant disturbances or failures do not compromise the system's ability to safely shut down the plant and maintain it in a shutdown state.

The standard encompasses multiple types of electrical analyses, including:

- Load flow studies, which assess steady-state operation to ensure system voltages remain within acceptable limits.

- Transient and dynamic studies, which determine the system's response to faults or disturbances.
- Short-circuit studies, ensuring that the electrical protection system is adequate for fault detection and isolation.
- Protection coordination to ensure proper system response during electrical faults and to minimize damage while maintaining power availability for essential plant functions.

Notably, IEC 62855:2016 does not cover specific digital controller analyses or environmental conditions (e.g., temperature, seismic events), which are addressed by other standards such as IEC 61513 for electronic controls. Additionally, the standard does not focus on personnel safety or reliability improvements through redundancy or probabilistic risk assessments (PRA), although it acknowledges that redundancy enhances reliability.

By addressing the design, operation, and modification of NPP electrical systems, IEC 62855 provides a structured framework for ensuring that electrical power systems are capable of performing essential safety functions under all operating and accident conditions. As such, it is a critical reference for maintaining the safety, reliability, and resilience of nuclear power plant operations.

2.1.2 IEC 63046:2020 - NPPs - Electrical power system - General requirements

IEC 63046:2020 establishes the essential requirements and recommendations for electrical power systems in NPPs, encompassing both interruptible and uninterruptible electrical power systems [2]. This standard ensures that electrical power systems, including those supporting Instrumentation & Control (I&C) systems, are designed to meet rigorous safety and operational goals. It aligns with nuclear safety objectives, providing guidance for maintaining reactor safety while supporting power generation for the grid.

IEC 63046 emphasizes the need for comprehensive and precise requirements, derived from plant safety goals, to ensure that the architecture of the overall electrical power system is robust and reliable under normal operation, anticipated operational occurrences, design basis accidents (DBAs), and design extension conditions. Key areas of focus include:

- Supporting reactor safety systems that are critical to nuclear safety, with particular attention to redundancy, independence, and Defense-in-Depth principles.
- Active and reactive power support, ensuring grid stability, and enabling nuclear power plants to provide electro-mechanical inertia to the grid.

Key Provisions of IEC 63046:2020 include:

- The standard establishes the requirements for implementing electrical power systems in NPPs, ensuring that the design aligns with safety requirements while supporting both critical safety functions and the plant's contribution to the grid.

- The architecture of the electrical power system must integrate Defense-in-Depth strategies, applying redundancy and independence in line with nuclear safety classifications. The architecture must ensure that failure of any single component does not compromise the plant's ability to maintain safe operation.
- The standard specifies requirements for coping with events such as Loss of Off-site Power and Station Blackout. Adequate design provisions are required to maintain the functionality of safety systems, including backup power supplies, during these conditions.
- IEC 63046 provides a lifecycle approach to the design, implementation, and maintenance of electrical power systems. This framework includes guidelines for design, verification, integration, commissioning, and ongoing maintenance, ensuring the system's reliability over the plant's entire operational life.

Design and Operational Guidelines:

- The standard provides functional performance requirements, ensuring that electrical power systems maintain their ability to support reactor safety under normal and abnormal conditions. It includes criteria for voltage stability, protection from electrical disturbances, and integration with supporting systems like Heating, Ventilation, and Air Conditioning (HVAC) and Instrumentation and Control (I&C).
- The design of both types of power subsystems is addressed, with guidelines for ensuring reliable power supply to critical systems during grid disturbances or internal plant failures. These systems are essential for maintaining continuous operation of safety systems and mitigating the impact of electrical power loss.
- The standard outlines the coordination needed between NPP electrical systems and external grid operators, including requirements for fault ride-through capabilities, frequency response, and interaction with other grid-connected power plants.

Scope of Application:

IEC 63046 is applicable to both new NPPs and upgrades or backfitting of existing plants. For existing facilities, only relevant portions of the standard may be applied, depending on the scope of the project. The standard is designed to be flexible, providing guidelines for applying a subset of requirements to older plants, ensuring their continued safe operation.

IEC 63046:2020 emphasizes that while it provides broad guidelines for the overall electrical power system, it does not cover specific details of I&C systems or external transmission lines, which are governed by other IEC standards such as IEC 61513 for I&C systems and IEC 62855 for electrical power system analysis. Additionally, it does not address detailed power production requirements but highlights the interconnection between buses, generators, and loads within the safety-classified elements of the power system.

Interaction with Other Standards:

IEC 63046 works in conjunction with other IEC and IAEA standards, defining how safety, electrical performance, and system maintenance are integrated into the broader nuclear power plant framework. By ensuring that all electrical systems meet the highest safety standards, IEC 63046 supports both reactor safety and grid reliability, playing a vital role in the continued safe operation of nuclear power plants.

2.1.3 IEC 61225:2019 - Requirements for Static Uninterruptible DC and AC Power Supply Systems

IEC 61225:2019 outlines the performance and functional characteristics of static uninterruptible power supply (SUPS) systems used in NPPs [3]. This standard is critical to ensuring the continuous, reliable power supply to systems important to safety, especially in the event of abnormal conditions or electrical disturbances on the site's AC distribution system. It ensures that static SUPS can protect connected equipment from voltage variations, based on the immunity concept.

Key Features of IEC 61225:2019 include:

- SUPS systems must protect all connected equipment (loads) from transients or perturbations on the AC distribution system. The design should guarantee uninterrupted power within specified tolerances for voltage, waveform, and frequency.
- The standard recommends a defense-in-depth strategy, ensuring that SUPS systems are designed to support both safety-critical and non-safety equipment. A graded approach to verification and validation ensures that system integrity is thoroughly tested across various operational scenarios.
- A key addition in this edition is the emphasis on protecting parallel-connected batteries during abnormal operating conditions. The standard mandates the use of appropriate isolation devices to prevent a single point of failure from affecting multiple divisions of the uninterruptible power supply system. This measure is crucial in preventing cascading failures that could compromise the reliability of the NPP's power system.

System Requirements:

IEC 61225:2019 provides guidelines for designing, implementing, and maintaining static SUPS systems. It emphasizes:

1. Functional and performance requirements for DC and AC SUPS systems, including inverters, battery chargers, converters, and bypass switches.
2. Design provisions for redundancy, isolation, and separation of power supply divisions to ensure that each division remains independent and can continue to operate even in the event of a failure in another part of the system.

The scope includes:

- System architecture and boundaries, covering both DC and AC systems with detailed specifications for inverters, battery chargers, and isolation mechanisms. SUPS systems must support the plant's safety functions even under degraded conditions like loss of off-site power or station blackout.
- The standard addresses how transients, electromagnetic interference (EMI), and load characteristics such as inrush current can affect supply quality. It includes provisions to mitigate these effects, ensuring that the power supplied to safety-critical systems is stable and meets design specifications.

Alignment with Other Standards:

IEC 61225:2019 is closely aligned with other related standards, such as IEC 61513, which sets out general requirements for instrumentation and control systems, and IEC 63046, which governs electrical power systems in NPPs. The standard also supports IAEA SSR-2/1, ensuring that the design, installation, and operation of SUPS systems meet international nuclear safety requirements.

Maintenance and Testing:

The standard emphasizes the importance of:

- Regular testing to ensure that SUPS systems retain their functional performance. Staggered testing is recommended to ensure that system redundancy is not compromised during maintenance.
- Ageing management to mitigate potential degradation of components such as batteries and capacitors over time, ensuring reliable operation throughout the plant's lifecycle.

IEC 61225:2019 is vital for maintaining the reliability and safety of power systems in nuclear power plants, particularly during abnormal conditions. It ensures that all connected loads, including those critical to reactor safety, are protected from disturbances on the AC distribution system. By specifying robust design, maintenance, and testing criteria, this standard plays a key role in upholding the integrity of power supply systems, safeguarding both routine and safety-critical operations in nuclear facilities.

The IEC standards governing electrical power systems in NPPs are structured into different levels based on their scope and applicability. IEC 63046 is classified as a Level 1 standard, defining the fundamental principles for electrical systems in NPPs.

In alignment with this classification, IEC 61513 also falls under Level 1, providing high-level safety and design criteria for electrical and control systems.

Standards that further refine these principles at Level 2 include:

- IEC 61225: Specifies requirements for electrical supplies in NPP safety systems.
- IEC 62855: Focuses on the analysis and verification of electrical power systems in NPPs, ensuring they meet safety and operational requirements.

2.2 SAFETY AND RELIABILITY CRITERIA FOR DC SYSTEMS

DC systems in nuclear power plants are integral to ensuring the continuous availability of power for critical systems, particularly in emergency or shutdown scenarios. Safety and reliability are paramount, and the following criteria must be observed to meet international standards and ensure the safe operation of nuclear power plants:

- DC systems, including generator excitation bridges and UPS systems, must maintain continuous and reliable power to safety-critical loads, such as reactor cooling systems, control systems, and emergency lighting [4]. UPS systems, particularly static SUPS, must function without rotating parts, ensuring a more stable and reliable power supply with minimal mechanical failure risks.
- Redundancy in DC systems is essential to ensure that a failure in one section of the power supply does not jeopardize overall system performance. IEC 61225 emphasizes the requirement for isolating devices, especially for batteries connected in parallel, to prevent a single failure from affecting multiple divisions of the UPS system. This isolation is crucial for maintaining the integrity of the plant's power supply during abnormal conditions [5].
- The defense-in-depth concept requires that all DC systems, not just those deemed critical to safety, are designed with graded levels of protection and validation [6]. This ensures that any power supply failure is adequately mitigated, and the overall safety of the plant is maintained.
- DC power systems should be flexible and scalable to accommodate future modifications or expansions. Standards such as IEC 62855 and IEC 63046 emphasize the importance of verifying system adequacy when modifications are introduced, ensuring that any new installations do not compromise the reliability of the existing power systems.
- Protection against electrical transients is a key requirement for DC systems in nuclear power plants. According to IEC 61225, the static SUPS must shield connected equipment from transients in the AC distribution system, ensuring that sensitive safety and control systems are not disrupted by power fluctuations.
- In addition to international standards, national regulations must be considered. DC systems in nuclear plants must comply with specific national safety codes and operational guidelines, ensuring that all aspects of their design, operation, and maintenance align with regional safety requirements.

Adhering to the safety and reliability criteria outlined in international standards such as IEC 62855, IEC 63046, and IEC 61225 ensures that DC systems in nuclear power plants remain robust, reliable, and capable of maintaining safe operations even under adverse conditions. These criteria contribute to the overall safety culture

within nuclear power plants, helping to prevent accidents and ensure that power supply interruptions do not compromise plant safety.

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3 State-of-the-Art Technological Solutions

This section provides an overview of state-of-the-art power electronic technological solutions that can be used for the NPP system (a typical example from [1], as shown in Fig. 3.1), so as to replace the thyristor chargers and inverters and achieve better performance with enhanced controllability. The solutions are presented from device level to system level, where the converter topologies and control (both DC/DC for chargers and DC/AC for backup supply), power semiconductor devices, and the considerations for reliable operations are included.

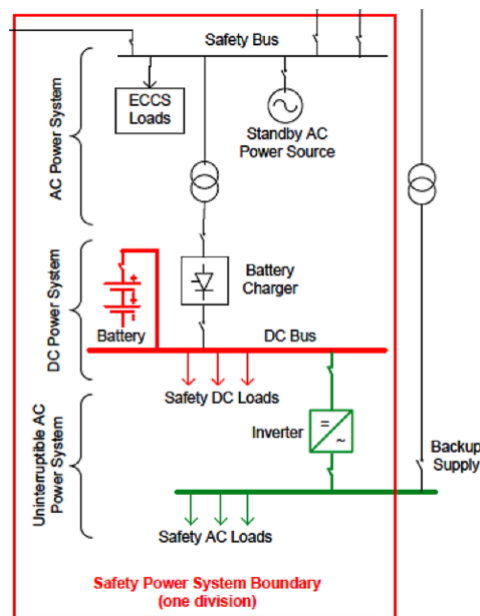


Figure 3-1 Power electronic converters in the studied system [1]

3.1 DC/DC POWER ELECTRONICS CONVERTERS FOR CHARGERS

In general DC/DC applications, various aspects need to be considered and adapted to the applicational requirements, which basically include [2, 3]: (1) rated voltage (both V_{in} and V_{out}) and power, (2) voltage gain (V_{out}/V_{in}) or capability of voltage regulation, (3) voltage polarity, (4) voltage ripple, (5) power efficiency, (6) galvanic isolation, (7) control methods, (8) dynamic performance, and (9) electromagnetic compatibility (EMC).

Several fundamental DC/DC converter topologies based on controllable power semiconductors (insulated-gate bipolar transistors (IGBTs), metal-oxide-semiconductor field-effect transistors (MOSFETs), etc.) are included in the references [4, 5], which are summarized as Table 3.1. The following applicational features can be concluded based on the differences of the topologies:

Number of power devices (esp. power semiconductors):

- Smaller number of devices: (1) easier to implement and simpler control structure, (2) higher energy efficiency, (3) lower cost of development, and (4) less prone to device wear-out or other failures.

- Larger number of devices: (1) more freedoms of control, and (2) better performance (e.g. voltage ripple).

Use of transformers for electrical isolation:

- Non-isolated: (1) easier to implement and simpler control structure, (2) higher energy efficiency, (3) lower cost of development, (4) smaller size (less space and weight), and (5) no transformer-wise risks.
- Isolated: (1) more flexibility of voltage regulation, and (2) galvanic isolation (more noise immunity, and safer in high-voltage scenarios).

where, non-isolated converters are not preferred for NPPs accounting for safety.

Table 3.1 Fundamental DC/DC converter topologies

Non-Isolated Converters				
Converter Type	Topology	Equivalent Voltage Gain	Maximum Voltage Stress	Polarity
Buck		$M(D) = D$ (stepping-down)	V_g	Consistent
Boost		$M(D) = \frac{1}{1-D}$ (stepping-up)	V	Consistent
Buck-boost		$M(D) = -\frac{D}{1-D}$	$V_g + V$	Inversed
Isolated Converters				
Converter Type	Topology	Equivalent Voltage Gain	Maximum Voltage Stress	
Full-bridge		$M(D) = nD$	V_g	
Half-bridge		$M(D) = \frac{1}{2}nD$	$\frac{V_g}{2}$	

Among the others, dual-active-bridge (DAB) converter and its variance, dual-bridge based series-resonant (SR) converter, are also commonly-used DC/DC converters, which are advantageous with high flexibility in voltage regulation and performance optimization (esp. soft-switching (ZVS/ZCS) for minimizing the losses of power semiconductors). Besides, the size of DAB or SR converters can also be reduced compared to conventional isolated DC/DC converters, by using high-frequency transformers. Typical phase-shift DAB and SR converters are shown in Fig. 3.2 [6, 7], while the resonant tank of SR converters can also be configured in more complicated topologies like CLLC (for bidirectional power flow) [8], etc.

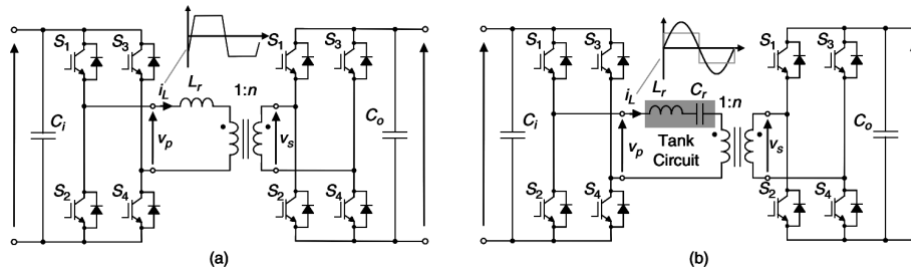


Figure 3-2 (a) Dual-active-bridge (DAB) converter and (b) SR converter (LLC topology)

The major difference between the DAB and SR converters is the resonant circuit, which leads to the difference in the transformer current (typically trapezoidal and sinusoidal, respectively). Consequently, the two topologies have the following technical features [6-9]:

Table 3.2 Comparisons of DAB and SR converters

	DAB Converter	SR Converter
Energy Efficiency	Generally high	High at heavy loads, but drops at light loads
Complexity of Development	Relatively more complex control	Relatively simpler control but more complex resonant circuit
Size and Weight	More compact with high-frequency transformer	Larger due to the resonant tank
Voltage Conversion Range	Wider	Narrower, but can be optimized for specific operating conditions

Specifically, for battery operations, apart from the functional and efficiency-wise requirements, there are a few additional features that can be essential or preferable [2, 3], that could be referred to:

1. *Adaptability to fluctuating input voltage* which varies along with the state-of-charge (SoC) of batteries. A more detailed explanation of the SoC of batteries is provided in Subsection 3.4.
2. Capability of *bidirectional operation* if both charging and discharging are desired (DAB converter, and Buck-boost, Cuk and single-ended primary-inductor converters (SEPIC) in Table 3.1 can be operated in bidirectional mode).
3. *Modularity and scalability* so that the converter modules can be added or removed flexibly in accordance with the change of battery modules or cells.
4. Capability of *securing the battery cells* from over voltage, over current and over discharging, and *thermal management* to maximize the use life of battery.
5. Ability to *survive potential severe mission profiles* from the environment, where the quality of implementation and manufacturing takes a critical role.

In short, we expect DAB converter to be a typical solution, while it should always be subject to the functional and reliability requirements of the NPP, e.g., conclusions inferred from the interviews.

3.2 DC/AC POWER ELECTRONICS INVERTERS FOR BACKUP SUPPLY

DC/AC inversion requires an opposite direction of power flow compared to AC/DC rectifiers, and controllable devices are required instead of diodes. In modern applications, as fully-controllable devices (like IGBTs and MOSFETs) are well developed, the basic inverter topologies are the half-bridge and full-bridge converters, as shown in Fig. 3.3.

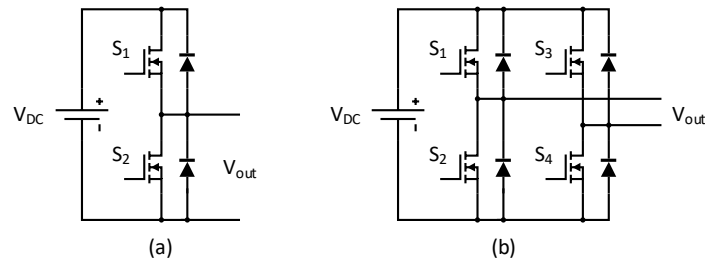


Figure 3-3 Single-phase DC/AC inverters: (a) half-bridge inverter and (b) full-bridge inverter

To output a sinusoidal voltage, they operate according to the following general principles:

1. **Pulse-Width Modulation (PWM):** The power semiconductors operate as high-speed switches (typically 10-20 kHz for IGBTs and up to 25-500 kHz for MOSFETs) to generate voltage/current pulses at the AC side, of which the switching-frequency average follows sinusoidal waveform, thus mimicking the AC voltage/current. This is the Pulse-Width Modulation (PWM).
2. **Complementary switching:** In each leg, the devices in the upper and lower half operate in the complementary (opposite) states. Considering that the devices are not ideal switches and need time to shift between on- and off-states, dead-times (turn-on delays) are applied to all devices to avoid short circuits.
3. **Filtering and smoothing:** To obtain smooth sinusoidal waveform out of the pulses, normally an LC filter is applied to grid-forming cases (when needed to operate as a voltage source), and an L (or LCL) filter is applied to grid-following cases (when needed to operate as a current source or load).

whereas they have the following key differences:

1. Full-bridge inverters have 4 switches, which is twice that of half-bridge inverters. Hence, full-bridge inverters have advantages in operational flexibility and functionality, while half-bridge inverters show higher reliability and more simplicity in implementation.

In practice, a basic drive strategy for full-bridge inverters is to align the switching states of S1 with that of S4, and S2 with S3, while S1 and S2 follow the same modulation as those in half-bridge inverters.

2. The maximum amplitude of V_{out} is half of the input DC voltage for half-bridge inverters, and full input DC voltage for full-bridge inverters.

Similarly, maximum voltage stresses on the power devices in full-bridge inverters (V_{dc}) are also double of that in half-bridge inverters ($V_{dc}/2$).

Three-phase DC/AC inverter topologies are shown in Fig. 3.4 [10, 11]. Based on single-phase inverters, three phase legs are connected in parallel, and a 120° difference is imposed between each two phases, forming the three-phase three-line (3P3L) structure. If the neutral line is needed, common practices include (1) leading the neutral line from the middle point of the DC bus, or (2) leading the neutral line from the common point of the capacitor branch of three-phase output filter.

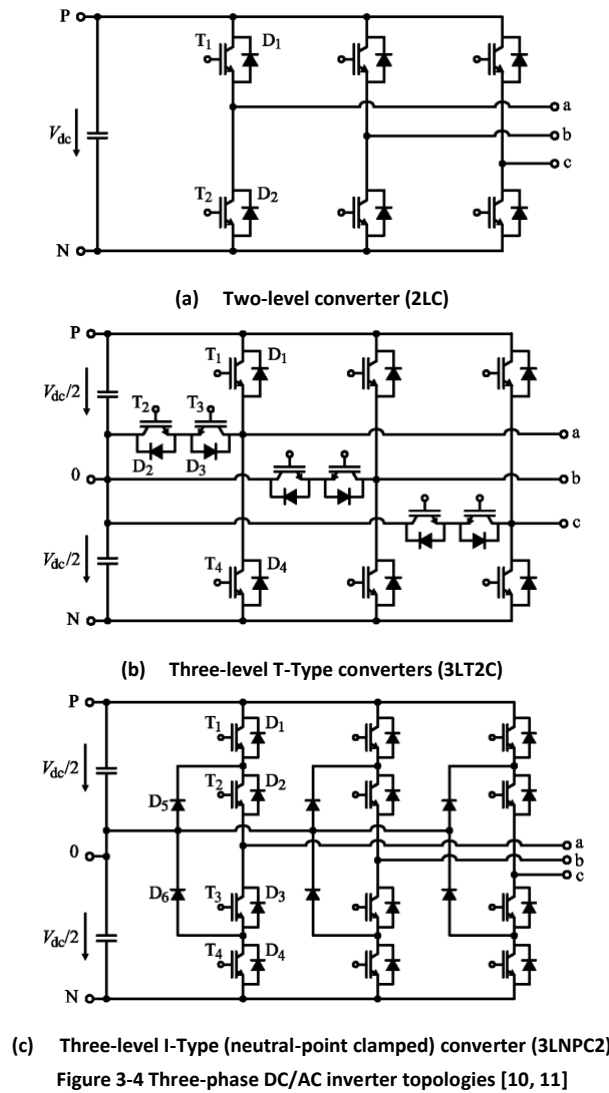


Figure 3-4 Three-phase DC/AC inverter topologies [10, 11]

Widely used topologies include two-level converter (2LC), three-level T-Type converters (3LT²C) and three-level I-Type (neutral-point clamped) converter (3LNPC²). They have the following features and differences:

Table 3.3 Comparisons of DAB and SR converters

	2L Converter	3L T-Type Converter	3L I-Type Converter
Voltage Levels	Two ($\pm V_{dc}/2$)	Three ($0, \pm V_{dc}/2$)	Three ($0, \pm V_{dc}/2$)
Harmonics	Higher (more filtering needed)	Lower (less filtering needed)	Lower (less filtering needed)
Power Efficiency	Relatively lower	Relatively higher	Relatively higher
Reliability	Relatively higher (fewer components)	Relatively lower (more components)	Relatively lower (more components)
Complexity of Implementation	Low	Relatively higher	Relatively higher
Typical Applications	General low- to medium-power applications	Medium- to higher-power applications, incl. solar inverters, motor drives and UPS systems	High-power applications like renewable energy systems and motor drives, etc.

Similarly, converters with more voltage levels have been introduced in [12], to achieve even better harmonic performances. But considering their higher complexity and more targeted application scenarios, they are not recommended for the studied NPP application and not elaborated in more detail in this report.

In medium- to high-voltage (MV/HV) applications, modular multilevel converters (MMC) are also used [13, 14], to reduce the voltage stress on individual power device by connecting sub-modules in series, as shown in Fig. 3.5. Commonly-used sub-modules include half-bridge and full-bridge topologies, which are similar to the single-phase inverter (a half-bridge sub-module is exemplified in the figure).

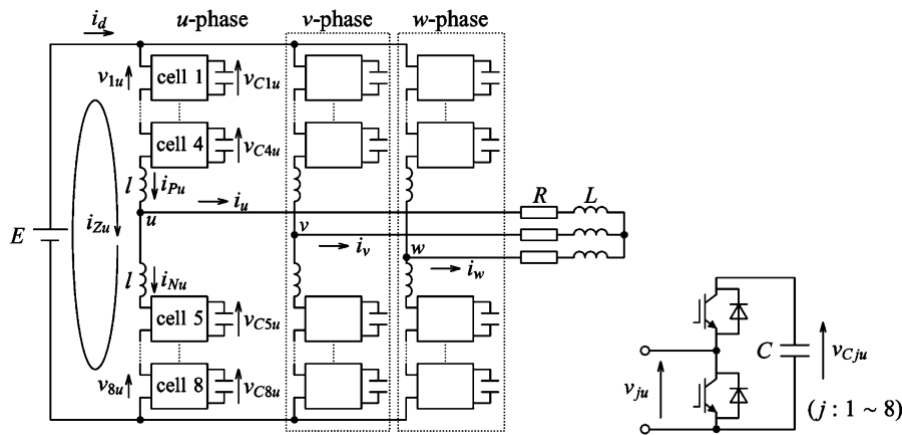


Figure 3-5 Three-phase modular multilevel converter (MMC) [13, 14]

MMCs have the following advantages:

1. Each sub-module can be independently controlled, allowing for high flexibility and scalability which are suitable for different power and voltage levels. Multiple control targets can also be achieved simultaneously.
2. The modularized structure simplifies the implementation and maintenance of MMCs, and the capability of fault-tolerance can be achieved by reserving redundant sub-modules, bypassing faulty modules and conduct replacement without impacting the entire converter.
3. With multilevel topology, MMCs can produce a multilevel output voltage and generate waveforms highly close to sinusoidal shape with minimum harmonic distortion. To this end, the EMI performance can be further improved where the requirement on filter design is the lowest, and the acoustic noise can be further mitigated with less harmonics and smaller-scale filters.
4. With capacitors in each sub-module, energy storage is allowed within MMCs, which can enable short-term support during transient disturbances and contributes to stable operation, e.g., under fluctuating input conditions.

Meanwhile, MMCs have disadvantages in, e.g., higher initial cost, more complicated control strategies, larger size and weight, and lower power efficiency in low-power scenarios. The aging of sub-module capacitors turns out to be an additional consideration in MMCs which however does not exist in basic DC/AC inverters.

3.3 OPTIONS FOR POWER SEMICONDUCTOR DEVICES

Power semiconductors (incl. both diodes and transistors) are the key part in power conversion, which primarily include the following *silicon* (Si) devices: diodes, thyristors, power bipolar junction transistors or giant transistors (BJTs/GTRs), insulated-gate bipolar transistors (IGBTs), metal-oxide-semiconductor field-effect transistor (MOSFETs), insulated-gate commutated thyristors (IGCTs), and gate turn-off thyristors (GTOs) [15-22]. In recent years, wide-bandgap (WBG) semiconductors utilizing silicon carbide or gallium nitride (SiC/GaN) materials are also being developed and becoming more and more popular in power electronics applications, showing outstanding improvement in general performances.

Diodes are the most fundamental devices, in which there is a PN node blocking current in inverse direction and allowing power to flow only in single direction. Hence, diodes can be used in AC/DC rectifiers but not suitable for DC/AC inverters.

Among the other devices except for diodes, MOSFETs have the inherent capability of bidirectional current flow, while IGBTs are normally manufactured with free-wheeling (anti-parallel) diodes in practice, which also allow for inverse current flow. In PWM-based power conversion applications, the power semiconductor devices can be regarded as switches, which, as per Fig. 3.6 (where IGBT is taken as an example), corresponds to the switch between active region (on state) and saturation region (off state).

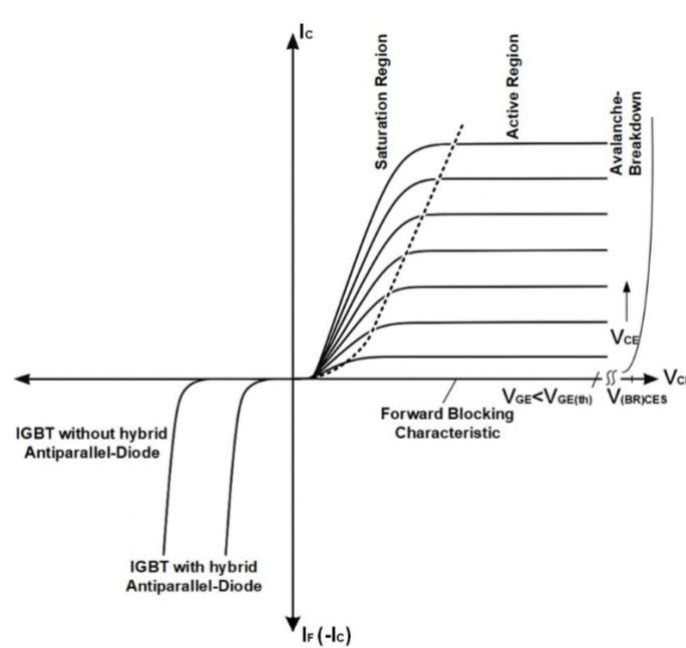
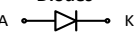
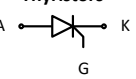
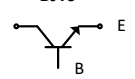
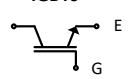
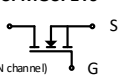
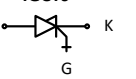
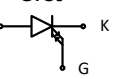


Figure 3-6 Output (V-I) characteristics of an IGBT (N-channel) [16]

A brief summary and comparison of the key features of the other power semiconductor devices is given as follows in Table 3.4.

Table 3.4 Summary of the key power semiconductor devices [15-22]

	Diodes 	Thyristors 	BJTs 	IGBTs 	Si MOSFETs 	IGCTs 	GTOs 	WBG Devices: SiC/GaN MOSFETs
Gate Control	Not controllable (totally passive)	Gate current, turn-on only	Base current	Gate voltage (v_{GE}), fully controllable	Gate voltage (v_{GE}), fully controllable	Gate current, turn-on and turn-off	Gate current, turn-on and turn-off	Gate voltage (v_{GE}), fully controllable
Switching Speed	Highest	Slow	Medium	Medium	High	Medium	Slow	Highest
Typical Switching Frequency	Very high (up to MHz)	Low (less than kHz)	Low to medium (max several kHz)	10-20 kHz	Max 1 MHz	Low to medium (max several kHz)	Low (less than kHz)	Max several MHz
Switching Losses	Very Low (w/o turn-on loss)	High	High	Moderate	Low	Moderate	High	Lowest
Conduction Losses	Low	Low	High	Moderate	Low	Low	Low	Lowest
Typical Voltage Ratings	Various (up to several kV)	Very High (up to several kV)	Medium (up to several kV)	High (up to several kV)	Medium (less than kV)	Very High (kV level)	Very High (kV level)	Very High (up to several kV for SiC, less than kV for GaN)
Typical Current Ratings	Various (up to hundreds A)	Very High (up to several kA)	High (less than kA)	High (up to 1 kA)	Medium (max hundreds A)	Very High (kA level)	Very High (kA level)	High (up to 1 kA for SiC, up to 100 A for GaN)
Operating Junction Temperatures	Typically up to 150 °C	Up to 150 °C (over 200 °C for some design)	Up to 150 °C	Up to 175 °C	Typically Up to 175 °C	Up to 150-200 °C	Up to 150 °C	Up to 200-250 °C for SiC, up to 175 °C for GaN
Overloading (Voltage/Current) Capability	Low	Very High (can withstand transient surges)	Medium	Medium to High	Low to Medium	Very High (can well handle transient surges)	Very High (can well handle transient surges)	Very High (can well handle transient surges)
Main Advantages	Simplicity and very low cost	High power capacity	High current gain	High efficiency & controllability	High efficiency & controllability, fast switching	High power capability	High power capability	High efficiency & controllability, fast switching
Main Disadvantages	Unidirectional current flow and no controllability	Slow switching and not fully controllable	Slow switching and high conduction loss	Limitation in switching frequency	Limitation in voltage and power rating	Costly and needing specialized gate drives	Slow switching and high switching losses	Costly and needing specialized gate drives
Typical Applications	Passive rectifiers, freewheeling, and clamping circuits	High-power scenarios, e.g., industrial drives and HVDC	Low-power analog circuits or amplifiers	Industrial drives, converters and EVs	Industrial power supplies and converters	High-power scenarios, e.g., industrial drives and MV/HV grids	High-power scenarios, e.g., industrial drives and HVDC	Data centers, fast chargers, EVs and aerospace

Note: B = Base, C = Collector, E = Emitter, G = Gate, A = Anode, K = Cathode, D = Drain, S = Source.

Although SiC and GaN devices are recognized for their high efficiency and robustness, their adoption in NPPs remains limited due to stringent qualification testing, compliance with IEC standards (IEC 62855, IEC 63046), and the need to ensure compatibility with legacy silicon-based systems.

In [16], there is also a summary of the configurations of typical power semiconductor modules (IGBT modules as an example) that are available on the market, as shown in Fig. 3.7, which should be referred to as the hardware basis of the aforementioned converter topologies (both DC/DC and DC/AC):

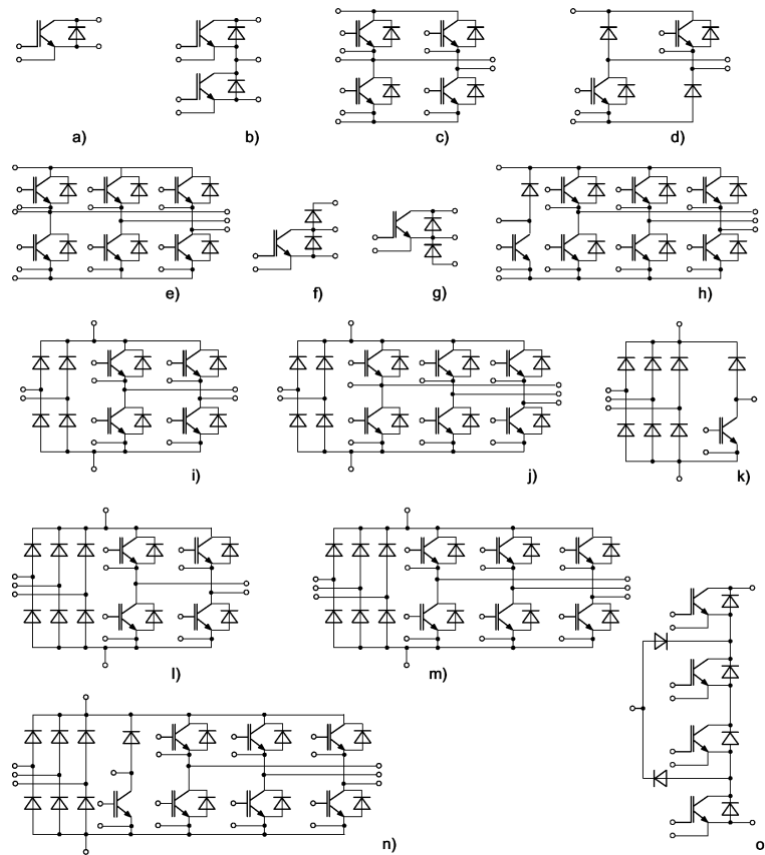


Figure 3-7 Typical configurations for power semiconductor modules available on the market [16]

Mainstream manufacturers for power semiconductors include: Infineon, Semikron, STMicroelectronics, ON Semiconductor (Onsemi), Mitsubishi, Toshiba, Vishay and Wolfspeed, etc. A few examples of the power semiconductors (both individual devices and modules) that are available in the market from Infineon and Semikron are shown below in Fig. 3.8. There are also full-converter solutions in the market including gate drivers and heat sinks & ventilators.



Figure 3-8 Exemplary power semiconductor modules available on the market from Infineon and Semikron, including different packages and functional accessories

Besides, the physics of conduction loss and switching loss are illustrated in Fig. 3.9, which result from the non-ideal switching behavior and turn-on/off delays. Apart from the influence in energy conversion efficiency, several further considerations are listed as below:

1. Higher switching frequencies increase switching losses, as the device spends more time transitioning and experiences more switching events per unit time.
2. Power losses convert to heat, which is a major consideration in the evaluation of system reliability. Higher power losses in general lead to higher junction temperatures and shorter device lifetime.
3. The power losses can be reduced by, e.g., (1) selecting the devices with low power losses, (2) leveraging soft-switching techniques, (3) properly designing the gate drive and circuit parasitic inductances/capacitances (which influence the turn-on/off time), and (4) improving the design of cooling for the devices.

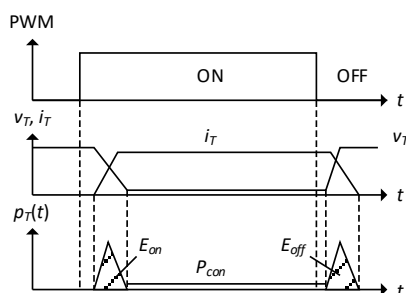


Figure 3-9 Typical illustration on conduction loss and switching loss of power devices

3.4 CONTROL TECHNIQUES FOR UPS SYSTEMS

The DC/AC inverter in the aforementioned Fig. 3.1 is used for interfacing the batteries as a backup Uninterruptible Power Supply (UPS) supporting the potential AC loads. Therefore, this section elaborates on the control techniques of UPS systems.

In general, the control of UPS systems can be divided into the following four aspects:

1. **Voltage regulation:** that generates the desired output voltage and maintains the output voltage against the input fluctuations.
2. **Battery management:** that handles the charging and discharging of the batteries and monitors the operation states of the batteries.
3. **Load management:** that ensures the quality of AC power supply and distributes the power efficiently among connected devices as per the needs.
4. **Bypass control:** that bypasses the UPS when the main power source is available for ensuring continuous power delivery, or when a maintenance of the UPS is needed.

The four aspects are elaborated as follows:

1. Voltage regulation

Basic voltage regulation for UPS DC/AC inverter is the double-loop voltage regulation, as shown in Fig. 3.10. The outer loop and inner loop are responsible for controlling the capacitor voltage and inductor current, respectively, and one of the most commonly used controllers is the proportional-integral (PI) controller $Out = K_p \cdot err + K_i \cdot \int err dt$.

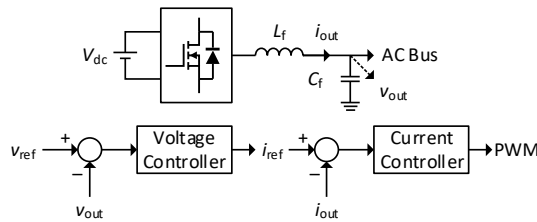


Figure 3-10 Double-loop voltage regulation for UPS DC/AC inverters

In some references, there are also advanced control strategies aimed at improving the output performances of the inverter, such as Fig. 3.11 from [23] utilizing feedforward paths to enhance the dynamic performances, where v_o and i_L correspond to V_{out} and i_{out} in Fig. 3-10, respectively.

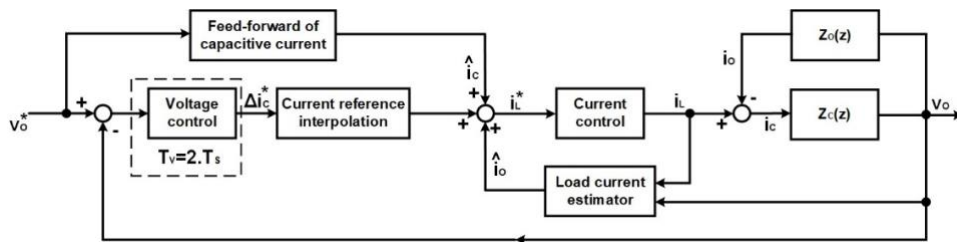


Figure 3-11 A voltage regulation strategy with enhanced dynamic performances from [23]

2. Battery management

A typical example of battery management is given in [24], as shown in Fig. 3.12, where the SoC of battery is monitored and controlled. It is also pointed out that for batteries consisting of multiple cells, balancing the SoCs of the battery cells can extend the overall lifetime of the battery system.

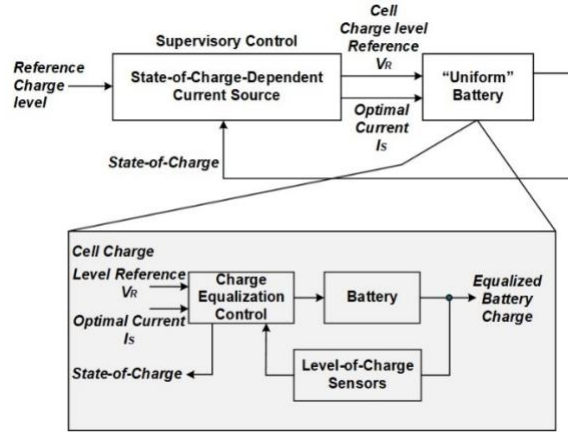


Figure 3-12 A battery management strategy from [24]

Further control targets for battery management can include: (a) state-of-health (SoH) monitoring of batteries, (b) energy efficiency optimization, (c) fault detection and over-voltage/current/temperature protection, etc.

3. Load management

Load management involves the coordination of both source and load sides. Source-side management refers to, e.g., the coordinative distribution of load among sources connected to the same AC bus, which is similar to the coordinative control in microgrids [25, 26] and especially the various grid-forming control strategies. Specifically, typical load management include basic centralized power control, decentralized droop control [27, 28] & virtual-synchronous-generator (VSG) control [29, 30] that mimic the P - f / Q - V relationships or inertia of synchronous generators, respectively, and virtual-impedance-based control [31] that aims at enhancing system stability. It is also possible to formalize other hierarchical control objectives based on needs.

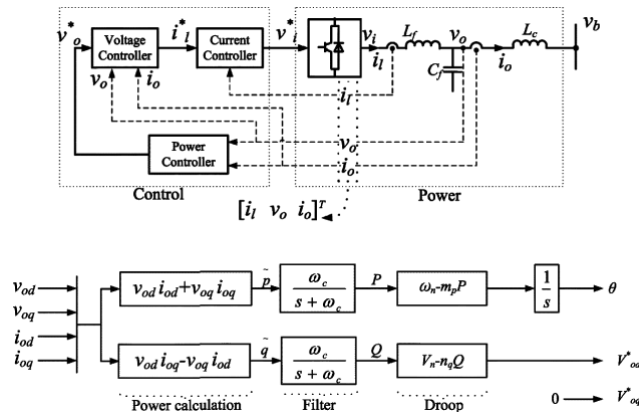


Figure 3-13 Droop control strategy from [27], where the angle θ is the integral of angular frequency $\omega=2\pi f$

Meanwhile, load-side management strategies may require the scheduling of loads based on individual priority, which can be, e.g., load shifting or load shedding, time-based scheduling or response to load demands.

4. Bypass control

Bypass control can be implemented via installation of alternative switches or control of interfacing converters to bypass or block the batteries during normal operation (load supplied by utility mains) or maintenance (load supplied by backup batteries) [32, 33]. Several examples are given in Fig. 3.14, where (a) and (b) use double-throw (DT) and single-throw (ST) switches, respectively, and (c) leverages the controllability of bidirectional DC/AC inverter by handling the PWM drive signals.

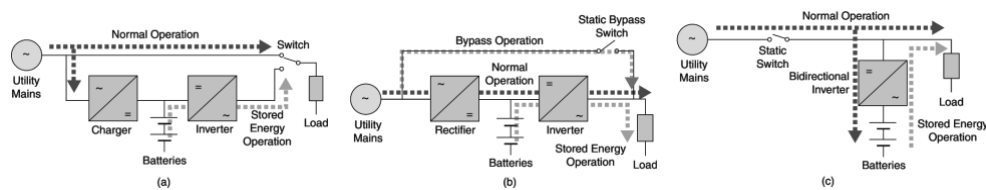


Figure 3-14 Typical bypass control strategies from [32]

The three structures are compared as follows:

Table 3.5 Comparisons of the bypass control strategies in Fig. 3.14

Strategy (a)	Strategy (b)	Strategy (c)
• Low cost & low complexity for implementation • Most reliable bypassing • Slowest response & most space with mechanical structure • Delay & occasional downtime of load may exist	• Low cost & low complexity for implementation • Downtime of load may be managed manually (flexible switching in/out for both load & batteries) • Slow response & large space due to mechanical structure	• Fast response and seamless switching with power electronic parts only, small in size and little space required • Complexity in control implementation • More maintenance required, highest installation cost

Among them, (b) or (c) are more suitable for NPPs than (a) as the battery must normally be connected to the feeding path.

3.5 CONTROL FOR RELIABILITY AND FAULT TOLERANCE STRATEGIES

Reliability and fault tolerance are paramount in the operation of power electronic systems in NPPs, where uninterrupted performance is critical. Control strategies in these environments must ensure that the systems are resilient against both internal failures and external disturbances, such as voltage fluctuations.

3.5.1 Fault Detection and Isolation (FDI) Systems

A central element of maintaining reliability is the use of FDI systems. These systems monitor real-time operational data, such as voltage, current, and temperature, using sensors integrated into power modules like rectifiers and inverters. Any detected anomaly triggers an immediate isolation response to prevent fault propagation throughout the system. FDI systems are critical in nuclear safety systems, where they help isolate faulty components and activate redundant systems before a minor fault escalates into a system-wide failure [34]. Advanced methods like sliding mode observers, which can accurately estimate the state of the system even in the presence of faults, are now widely used. These methods allow for the real-time identification of actuator and sensor faults, ensuring continuous, fault-tolerant operation in NPPs. Fig. 3.15 shows the structure of a sample conventional fault detection (FD) system for the high-voltage power supply (HVPS). The converter shown in this figure is an inverter. The FD system includes a current sensor that measures the load current, a buffer that isolates the sample signal, a low-pass filter that suppresses the noise impacts, a comparator for detecting the current increment and comparing it with the threshold value, and a latch for storing the state information. In normal conditions, the output of comparator is -1 and the protection system is inactive. When a short-circuit fault occurs, then the load current increases and exceeds the threshold value. As a result, the output of comparator becomes +1, the short-circuit fault is detected, and the protection system is activated.

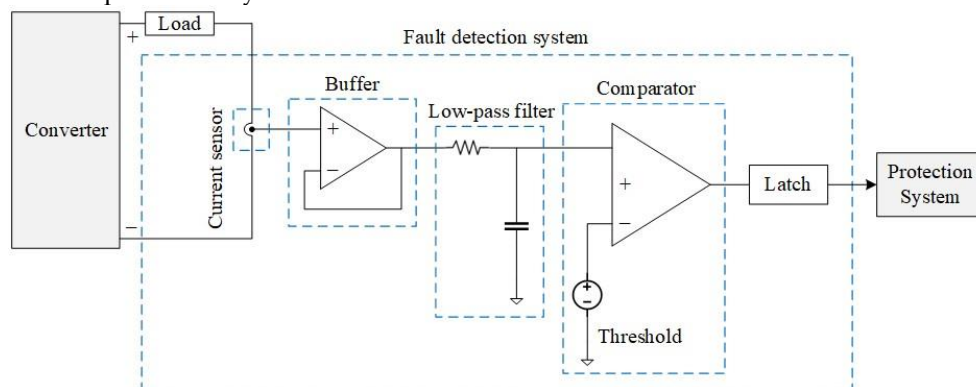


Figure 3-15 Conventional FD system for the HVPS

3.5.2 Redundancy and Robust Design

Redundancy plays a crucial role in fault tolerance. By having multiple independent systems or components that can perform the same function, NPP systems can continue operating even if one component fails. For example, in rectifiers and UPS systems, redundant modules are integrated into the design to take over in the event of a failure, ensuring uninterrupted power supply to critical systems [35]. Typically, no fault due to overload is observed in the NPPs.

Figures 3.16 to 3.18 illustrate various configurations and operational states of a converter with redundancy. Fig. 3.16 shows a converter, and its redundant module (another converter with switch) equipped with isolating switches, showing the basic setup for redundancy. Fig. 3.17 demonstrates the active redundancy setup, where (a) both converters are functioning normally, and (b) Converter 1 has failed, allowing Converter 2 to continue supplying the load. Fig. 3.18 shows the standby redundancy configuration, with (a) Converter 1 operating while Converter 2 is in a failed state, and (b) Converter 1 failing and Converter 2 taking over to ensure uninterrupted load supply. These figures collectively represent the redundancy strategies in power conversion systems for improved reliability.

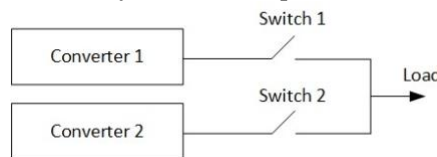


Figure 3-16 A converter and its redundant module with isolating switches

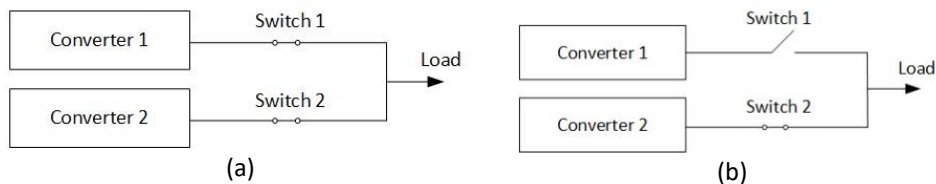


Figure 3-17 Two possible states for a converter with active redundancy: (a) both converters are normal, (b) converter 1 is failed

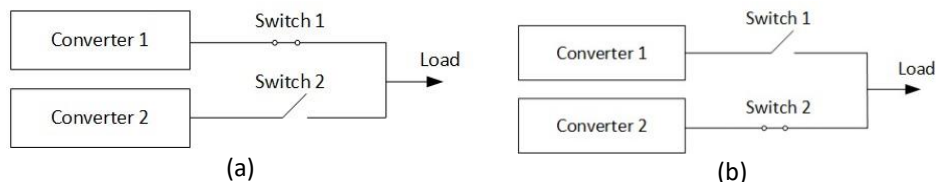


Figure 3-18 Two possible states for a converter with standby redundancy: (a) converter 1 is operated and converter 2 is failed, (b) converter 1 is failed and converter 2 is operated [36]

1. Serial redundancy

In a serial configuration like Fig. 3.19 (a), all converters share the load voltage and are rated for the same nominal current. Redundant modules can either operate at reduced voltage or be bypassed, activating only during a fault. The bypass is a crowbar, serves both as a protection and active bypass, responding to sudden voltage rises. Reliability is essential, as the switch must function effectively as a protection crowbar without triggering during normal operation.

2. Parallel redundancy

In a parallel configuration, as shown in Fig. 3.19 (b), all modules operate at nominal voltage, sharing the load current. The bypass switch acts as a fuse when one of the modules fails into a short circuit, preventing it from drawing current from other modules. It must reliably open on sudden current surges but remain closed when a neighboring module fails.

3. Hot spare

The hot spare approach keeps a backup power converter ready to replace any failed unit. Upon detecting a failure, the spare can instantly replace the faulty converter,

minimizing Mean Time to Repair (MTTR). This switch can be manual or automated, as shown in Fig. 3.19 (c). Although mechanical switches may be used, the configuration becomes more complex when one spare supports multiple converters. If one converter fails, the hot spare bypasses it to maintain load connection, making this approach compatible with modular or redundant systems.

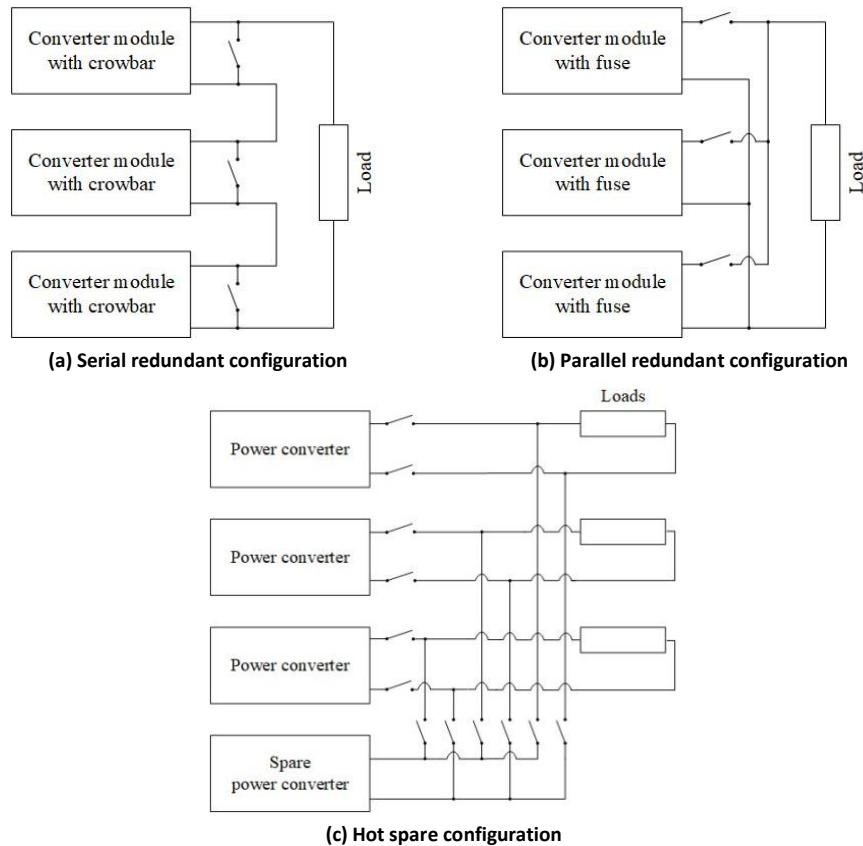


Figure 3-19 Serial and parallel redundant configurations

In addition to hardware redundancy, robust design principles are implemented at the component level. The robust design principle in power electronics for NPP applications includes redundancy in critical components, fault-tolerant control strategies, thermal management techniques, and compliance with nuclear safety standards to ensure system reliability under extreme conditions. Power electronics, particularly rectifiers and inverters, can be built using wide-bandgap semiconductors (such as SiC or GaN), which offer higher efficiency, lower thermal stress, and better resistance to voltage surges. This approach improves both the fault tolerance and overall durability of the components, as shown in Table 3.5.

3.5.3 Maintenance Strategies for Power Electronic Devices in NPPs

Maintaining power electronic devices in nuclear power plants is critical for ensuring the safety and efficiency of these facilities. The harsh operating conditions, coupled with the high demands for reliability and precision, necessitate robust maintenance strategies.

Power semiconductors in nuclear power plants may be subject to challenging operating conditions that can significantly impact their reliability and performance. Various environmental and operational factors—such as high temperature, voltage fluctuations, current surges, humidity, electrostatic discharge, and seismic activity—

can contribute to the degradation or failure of these components. In nuclear power plants, components must also be mechanically robust to withstand seismic shocks and vibrations as specified by relevant standards, ensuring continued operation during and after such events. These conditions lead to thermal stress, dielectric breakdown, and other mechanical and chemical stresses, which in turn can compromise the semiconductor's functionality and the stability of the overall system. Understanding these failure causes is essential for designing effective maintenance protocols and implementing strategies to enhance the resilience of power electronics, ensuring they operate safely and reliably in the demanding nuclear power plant environment.

Table 3.6 shows the main failure causes, mechanisms, and modes in power semiconductors. The root causes may be high temperature, overvoltage, overcurrent, humidity, and electrostatic discharge.

Table 3.6: Main failure causes, mechanisms, and modes in power semiconductors [37]

Root Cause	Failure Mechanism	Failure Modes
High Temperature	Thermal Runaway	Increased electrical resistance, excessive heating
	Thermal Stress	Thermal fatigue, delamination, cracks
	Hot Carrier Degradation	Increased threshold voltage, lowered breakdown voltage
Overvoltage	Dielectric Rupture	Electrical shorts, insulation failure, voltage breakdown
	Gate Oxide Breakdown	Gate leakage
Overcurrent	Overheating	Increased junction temperature
	Thermal Degradation	Dielectric breakdown, increased leakage current, reduced forward voltage drop
Humidity	Package Induced Failures	Moisture ingress, corrosion, delamination, package cracking
	Diffusion of Moisture	Electrical short, corrosion
Electrostatic Discharge	Thermal Failure	Increased temperature, thermal stress
	Gate Oxide Breakdown	Gate leakage, decreased breakdown voltage
	Junction Damage	Junction breakdown, increased leakage current
	Dielectric Rupture	Insulation breakdown, short-circuit
Radiation	Displacement Damage	Shift in threshold voltage, gain degradation, leakage current increase
	Ionizing Radiation Effects	Oxide charge buildup, timing errors, functional failures in logic circuits
Electromagnetic Fields	EMI-induced Switching Errors	Erroneous turn-on/off events, timing violations
	Capacitive/Inductive Coupling	Spurious signals, gate drive disruption
Software/Control Issues	Firmware/Software Bugs	Unstable operation, intermittent failures, lock-up states

In addition to the conventional physical and electrical stress factors listed in Table 3.6, other failure causes are relevant in specific environments such as nuclear power plants (NPPs). Radiation, particularly ionizing and neutron radiation, can induce degradation in semiconductor materials, leading to displacement damage or total ionizing dose effects, which in turn affect the electrical parameters of devices over time. Moreover, electromagnetic interference (EMI) from external sources or from within tightly integrated systems can result in unintended switching events or signal disturbances, potentially compromising power electronics reliability.

Another increasingly important aspect is the software/firmware running on power electronic control units. As modern devices rely more heavily on embedded

software for switching, protection, and communication, inconsistencies in firmware updates or latent software bugs may lead to asymmetric or unpredictable failure behaviors, especially over long operational lifetimes.

Maintaining power electronic devices in nuclear power plants is crucial due to the sensitive nature of the environment and the critical role these devices play in plant operations. **Table 3.7** outlines maintenance schedules for various power electronic devices commonly found in NPPs.

Table 3.7: maintenance schedules for various power electronic devices in NPPs [38]-[39]

Device	Maintenance Task	Frequency	Details
Inverters	Performance monitoring	Weekly	Monitor efficiency and output signals to ensure optimal performance.
	Cleaning	Quarterly	Remove dust and debris that could affect functionality.
Rectifiers	Electrical testing	Bi-annually	Test diode functionality and electrical output for signs of wear or failure.
	Thermal imaging	Annually	Identify hot spots which indicate potential component failures.
DC/DC Converters	Functional testing	Quarterly	Test under load to ensure stable operation and efficiency.
	Firmware updates	As needed	Update firmware to enhance performance and add new features.
AC/DC Converters	Calibration	Annually	Calibrate to ensure accuracy in conversion rates and output.
	Surge protection check	Bi-annually	Inspect and test surge protection devices to prevent damage from power spikes.
Battery Chargers	Battery health check	Monthly	Test battery capacity and replace batteries as necessary.
	Clean battery terminals	Quarterly	Clean terminals to prevent corrosion and ensure good electrical connections.
Diodes	Forward and reverse bias testing	Annually	Test diodes to ensure they are functioning correctly in both forward and reverse directions.
	Visual inspection	Bi-annually	Inspect for signs of thermal stress and physical damage.
Capacitors	Capacitance and leakage testing	Annually	Test capacitors for proper capacitance and leakage currents to ensure performance stability.
	Visual inspection	Bi-annually	Check for bulging, leakage, or discoloration that can indicate failure.
Voltage Regulators	Adjustments and alignment	Bi-annually	Adjust settings and alignment to ensure stable voltage output.
	Replacement of worn components	As needed	Replace components such as capacitors and resistors that show signs of wear.
Power Filters	Inspect and replace filters	Annually	Check filters for blockage or degradation and replace them if necessary.
	Check grounding and bonding	Bi-annually	Ensure all components are properly grounded and bonded to prevent electrical hazards.
General EMI Checks	EMI Testing	Annually	Perform detailed EMI tests to identify sources and levels of electromagnetic disturbances.
	Shield Integrity Check	Annually	Inspect the integrity of electromagnetic shielding on cables and equipment.
	Grounding System Check	Bi-annually	Verify the grounding system to ensure it provides effective EMI mitigation.
Cable and Wiring	Inspect and Test Cables	Bi-annually	Test for insulation integrity and proper shielding to prevent EMI leakage or susceptibility.
	Cable Routing Review	Annually	Review and optimize cable routing to minimize interference between power and signal cables.
Filters	Filter Inspection and Testing	Bi-annually	Test EMI/RFI filters to ensure they are effectively reducing high-frequency interference.
	Replace Worn or Ineffective Filters	As needed	Replace filters that fail testing or show signs of degradation.

Table 3.8 illustrates the various maintenance strategies for power electronic devices in nuclear power plants. These strategies include predictive maintenance such as condition-based maintenance, preventive maintenance such as time-based and used-based maintenance, reliability-centered maintenance, and corrective maintenance.

Table 3.8: Maintenance strategies for power electronic devices [40]

Strategy	Description	Key Features	Benefits	Timeline	Sub-strategies
Predictive Maintenance	Maintenance tasks are performed based on condition monitoring and predictive analysis.	Uses sensors, IoT technology, and data analytics to forecast failures.	Minimizes downtime by addressing issues before failure; optimizes maintenance resources.	Ongoing, with activities scheduled based on predictive analytics and equipment condition.	- Condition-Based Maintenance (CBM): Triggered by specific condition indicators. - Vibration Analysis: Detects abnormalities through vibrations. - Thermal Imaging: Uses infrared to find heat anomalies.
Preventive Maintenance	Scheduled maintenance based on time or usage intervals, independent of the equipment's current condition.	Regular inspections, component replacements based on a predetermined schedule.	Reduces unexpected failures, extends equipment lifespan.	Regularly scheduled (e.g., annually, biannually), based on operational data and manufacturer recommendations.	- Time-Based Maintenance: Scheduled at fixed intervals. - Usage-Based Maintenance: Scheduled based on equipment usage metrics.
Reliability-Centered Maintenance (RCM)	Focuses on maintaining system function by preserving equipment reliability.	Integrates a risk management framework, focuses on critical components.	Enhances reliability and safety, tailored to the criticality of system components.	Initial detailed analysis followed by periodic reviews and adjustments.	- Failure Modes and Effects Analysis (FMEA): Identifies potential failure modes and their impact. - Risk Priority Number (RPN): Prioritizes maintenance tasks based on risk.
Corrective Maintenance	Reactive approach where repairs are made after equipment failures occur.	Immediate fault identification and repair post-failure.	Potentially lower initial costs, immediate problem resolution.	No scheduled timeline; occurs as needed when equipment fails or malfunctions.	- Breakdown Maintenance: Immediate repair to restore function. - Root Cause Analysis (RCA): Identifies underlying causes of failures to prevent recurrence.

3.5.4 Protection from External Disturbances

Protection from external disturbances, such as grid voltage surges or EMI, is essential for maintaining reliability. Surge protectors, EMI filters, and fault-tolerant designs help mitigate the impact of such disturbances. These designs ensure that

disturbances upstream of the power electronics systems do not propagate downstream, safeguarding critical systems in the plant [41].

While modern UPS systems increasingly rely on digital protection mechanisms, practical experience suggests that analogue protection systems often provide faster response times due to their direct signal processing nature. However, digital protection systems offer advantages such as programmable settings, fault logging, and adaptive response to varying operating conditions. Furthermore, selectivity between the rectifier and inverter protection levels is crucial to avoid excessive overvoltage on the DC side. Proper coordination in protection circuits ensures that faults do not propagate between subsystems, enhancing overall system stability. Optimized circuit design and graded protection levels can help mitigate risks associated with voltage fluctuations in UPS applications.

Table 3.9 summarizes the control strategies employed in NPPs to enhance reliability and fault tolerance.

Table 3.9: Control Strategies for Reliability and Fault Tolerance in NPPs [41]

Strategy	Description	Application in NPPs	Benefits
Fault Detection and Isolation	Real-time monitoring of operational parameters with immediate fault isolation to prevent fault propagation	Applied to inverters, rectifiers, and DC/DC converters	Prevents system-wide failures, reduces downtime
Redundancy	Incorporating multiple independent systems or components to take over in case of failure	Redundant power supplies, rectifiers, and UPS systems	Ensures uninterrupted operation, increases fault tolerance
Predictive Maintenance	Monitoring component health and predicting failures using real-time data and machine learning algorithms	Real-time condition monitoring of rectifiers, inverters, and capacitors	Reduces unplanned downtime, extends component lifespan
Protection from External Disturbances	Use of surge protectors, EMI filters, and fault-tolerant designs to guard against external grid disturbances	Applied to power modules and UPS systems	Enhances resilience to voltage surges, grid disturbances, and electromagnetic interference
Robust Component Design	Use of advanced materials such as wide-bandgap semiconductors (SiC, GaN) for higher efficiency and reliability	Used in power electronics components such as rectifiers, inverters, and IGBTs	Improves thermal tolerance, extends operational life

While external disturbances are commonly addressed through surge protectors and EMI filters, internal dynamic interactions can also pose significant risks to system stability. In scenarios where the main synchronous generator is offline and the system relies heavily on power-electronic-dominated sources, the absence of rotational inertia can reduce system damping, making it more susceptible to control interaction instabilities or resonance phenomena. These effects can be particularly pronounced when multiple converters operate with tightly coupled control loops or different PLL settings.

Additionally, when power electronics are supplied by diesel generators, superimposed oscillations stemming from the reciprocating engine's torque pulsations (typically in the 1–50 Hz range) may propagate through the electrical system. Depending on their frequency and harmonics, these oscillations may interact with the switching harmonics of converters or with passive components

(e.g., filters and cables), potentially leading to resonances that affect voltage stability or even damage components.

The evolution towards higher switching frequencies in wide-bandgap power devices (e.g., SiC and GaN-based converters) introduces further complexity. While higher frequencies enable better dynamic control and smaller passive components, they also shift the system's resonance characteristics, possibly exciting new modes or creating interactions with slower mechanical oscillations. Thus, careful co-design of filter networks, control loop bandwidths, and system impedance shaping is critical to mitigate such interactions.

In Fig. 3.20, power electronic-based protection designs against external disturbances are illustrated. Image (a) depicts a surge protector, designed to shield electronic components from voltage spikes caused by external events such as lightning or switching transients. Image (b) shows an EMI filter that suppresses high-frequency electromagnetic noise, ensuring proper operation of sensitive circuitry. Image (c) illustrates a partially fault-tolerant system, where internal faults are detected and isolated via a Fault Detection and Isolation (FDI) unit, and reliability is enhanced through redundancy and a Fault-Tolerant Controller (FTC). However, this configuration does not offer full protection against all external disturbances. Scenarios such as voltage unbalance, frequency deviation, harmonic distortion, or grid asymmetry require additional mitigation strategies, including advanced control algorithms or system-level coordination. Therefore, while the illustrated setup improves reliability under specific conditions, it should be complemented with further protection schemes to achieve full fault tolerance in nuclear power plant environments.

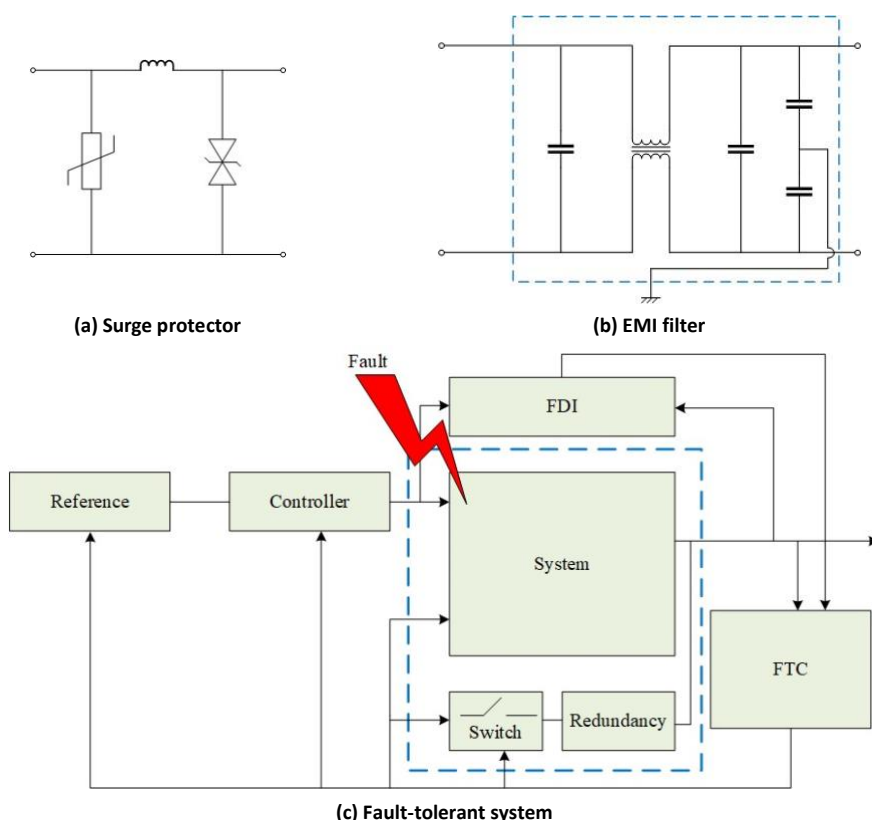


Figure 3-20 Power electronic-based protection designs against external disturbances

3.6 CONSIDERATIONS FOR COOLING AND CONDITION MONITORING

Efficient cooling and condition monitoring are fundamental to the long-term reliability and safety of power electronics systems in NPPs. Excessive heat can accelerate aging and lead to failure, while real-time condition monitoring allows for early fault detection and preventive maintenance.

3.6.1 Cooling Techniques for Power Electronics

Cooling is crucial in power electronics to manage heat generated by high-power components such as IGBTs, diodes, and capacitors. Different cooling techniques can be employed depending on the power density and operational requirements [42-44].

- **Air Cooling:** The simplest and most cost-effective method, using forced or natural convection. However, air cooling may be insufficient for high-power systems, where the heat dissipation capacity is limited.
- **Liquid Cooling:** More efficient than air cooling, liquid cooling systems circulate a coolant (e.g., water-glycol mixture) through cold plates attached to heat-generating components. This method is ideal for high-power density applications like inverter systems in NPPs.
- **Phase-Change Cooling:** Advanced cooling systems use phase-change mechanisms, such as heat pipes or two-phase immersion cooling, to achieve superior heat dissipation in space-constrained environments.

The choice of cooling method is influenced by the power density, environmental conditions, and specific requirements for thermal stability in NPP safety systems, as shown in **Table 3.10**.

Table 3.10: Cooling Techniques for Power Electronics in NPPs

Cooling Technology	Type	Characteristics	Advantages	Typical Applications
Air Cooling	Standard Heat Sinks	Utilizes fins to enhance air convection and heat dissipation.	Simple, cost-effective, no liquid mediums, easy to maintain.	Suitable for low to moderate heat loads in consumer electronics, computer CPUs, and some industrial devices.
	Heat Pipes	Incorporates sealed pipes that use phase change to transfer heat efficiently.	Enhances the efficiency of air cooling by spreading heat over a larger area rapidly.	Used in compact or high-performance applications like advanced computing and gaming systems.
Phase Change Cooling	Heat Pipe Assemblies	Uses a working fluid within sealed pipes that vaporizes and condenses to transfer heat.	High thermal performance, efficient at managing heat spikes, operates passively.	Critical in aerospace, military electronics, and high-performance computing where reliability and efficiency are paramount.
Liquid Cooling	Direct Liquid Cooling	Involves direct contact of coolant with heat sources via cold plates.	Superior cooling performance, handles high heat fluxes, precise temperature control.	High power density applications such as power inverters, high-performance servers, and electric vehicle power systems.
	Indirect Liquid Cooling	Coolant circulates through a heat exchanger separate from electronics.	Reduces risks of leaks damaging electronic components.	Suitable for large scale industrial applications and situations where direct contact cooling poses risks.

3.6.2 Thermal Management for Enhanced Longevity

The longevity of power electronics depends heavily on efficient thermal management [45]. Wide-bandgap semiconductors, such as SiC and GaN, can be used in NPP applications due to their ability to operate at higher temperatures and handle higher thermal loads. These materials reduce the thermal strain on components, thereby extending the operational life of systems like rectifiers and inverters.

In conjunction with these materials, advanced heat sink designs, thermally conductive materials, and improved packaging techniques help reduce thermal resistance and manage the heat load more effectively. This approach minimizes the risk of thermal failure, especially in high-power applications where excessive heat is a primary concern.

3.6.3 Condition Monitoring for Proactive Maintenance

Real-time condition monitoring is essential for early fault detection and system reliability. Key parameters such as temperature, current, voltage, and vibration are continuously monitored in critical components like power modules and rectifiers. Any deviation from normal operational ranges triggers alarms and allows operators to take corrective action before a fault develops.

The use of predictive analytics, based on machine learning algorithms, further enhances this process by identifying patterns that suggest imminent component failure. For example, gradual increases in operating temperature or fluctuations in voltage can indicate wear or degradation in semiconductors, capacitors, or other critical components.

In addition to cooling, condition monitoring systems play a vital role in maintaining operational reliability [46]. **Table 3.11** outlines the key parameters monitored in NPP systems, such as temperature, vibration, and electrical characteristics in real time as part of an online condition monitoring system. Real-time monitoring allows for early detection of anomalies, while predictive maintenance uses machine learning algorithms to forecast failures, improving overall system performance and reducing downtime.

Table 3.11: Condition Monitoring Systems for Power Electronics in NPPs

Monitoring Parameter	Method of Monitoring	Application in NPPs	Benefits	Challenges
Temperature Monitoring	Online monitoring using thermal sensors placed at key points (e.g., semiconductors, capacitors)	Inverters, rectifiers, and power converters	Prevents overheating, improves operational safety, and extends component life	Sensor degradation in extreme environments, increased initial costs
Vibration Monitoring	Online monitoring using accelerometers to detect mechanical stress and vibrations in rotating components.	Mechanical components, rectifiers, and inverters	Detects wear and tear early, prevents mechanical failure	False alarms, durability of sensors under harsh conditions
Voltage and Current Monitoring	Continuous online tracking of electrical parameters with sensors.	Power distribution systems, inverters, rectifiers	Identifies over-voltage and over-current conditions	Signal interference, sensor calibration and accuracy, potential for data overload

➤ Specifications for Variables and Condition Monitoring

Effective condition monitoring relies on detailed specifications at both the system and device levels. At the system level, managing thermal conditions involves real-time monitoring of key components such as capacitors, transformers, and power modules. Advanced cooling techniques, including liquid cooling or phase-change materials, can effectively dissipate heat in high-power-density applications. For vibration monitoring, accelerometers are used to detect mechanical stress or abnormal vibrations, particularly in inverters and other critical components. Establishing acceptable vibration thresholds aligned with international standards, such as those set by IEC and IAEA, ensures that systems can operate reliably under various conditions.

At the device level, parameters for converters and inverters must include efficiency ratings, voltage ripple thresholds, and voltage stress tolerance. For instance, achieving efficiency levels above 98% is common for modern systems. Real-time monitoring of key indicators such as junction temperatures, current spikes, and voltage deviations enables early fault detection, while predictive maintenance strategies based on machine learning can anticipate potential failures. Modular designs for converters simplify maintenance and replacements, reducing downtime and enhancing system resilience.

Furthermore, integrating real-time feedback mechanisms into monitoring systems allows operational parameters to adjust dynamically, minimizing the risk of faults. Predictive analytics, driven by sensor data, can detect patterns indicating wear or degradation in semiconductors and capacitors. This proactive approach ensures timely interventions, ultimately extending the operational lifespan of the system. By adopting these specifications and advanced condition monitoring techniques, the reliability and safety of power electronics in NPPs can be significantly enhanced.

3.6.4 Condition Monitoring Techniques for Power Electronics Components

Condition monitoring (CM) for power electronics components aims to acquire its operating characteristics. In [47], it is technically distinguished from *diagnosis* and *prognosis* as follows:

1. **Diagnosis** is to identify the root cause of a fault given that it has occurred.
2. **Prognosis** is to assess the health level of a component and predict the future health level.
3. **Condition monitoring** is to measure the operational metrics of a component and indicate appropriate actions when any of it drifts away from the normal conditions.

General condition monitoring approaches can be classified based on the following features [47-52]:

1. **Direct / indirect** approaches: In condition monitoring of power electronics components, direct approaches involve measuring parameters directly associated with the component's behavior, such as using vibration analysis to detect imbalances in rotating machinery. Conversely, indirect approaches

infer the condition of components by measuring variables elsewhere in the circuit; for example, partial discharge monitoring detects insulation degradation by measuring electromagnetic emissions or acoustic signals.

2. **Offline / online** approaches: Online monitoring is predominantly used in modern power electronics systems, including NPP applications, due to its ability to provide real-time condition monitoring without disrupting operations. Online methods enable continuous assessment of system health, early fault detection, and predictive maintenance strategies, reducing unexpected failures and improving system reliability. Offline monitoring, while still used in some cases (e.g., scheduled maintenance, deep diagnostics, and laboratory testing), is generally less preferred because it requires system downtime and component disassembly. This makes it less practical for critical applications where high availability and reliability are required, such as safety and control systems in NPPs. Thus, online monitoring is the preferred approach, particularly for predictive maintenance and fault detection in power electronics for NPPs.
3. **Signal- / model- / data-based** approaches: approaches based on characteristic signals and corresponding thresholds / based on calculation through mathematical models / based on data technologies (incl. statistical approaches and neural networks).
4. Types of variables (metrics) under measurement.

Some practical CM techniques for power semiconductors and capacitors, which are among the most fragile power electronics components, include [47-52]:

Table 3.12 Practical metrics for condition monitoring of power electronics components

Components	End-of-Life Metrics / Criteria	Typical Approaches
Power Semiconductors [47, 48]	Metrics dependent on the dominant failure mechanism, which may include R_{on} or $V_{CE, on}$, t_{on} or t_{off}, T_j, or V_{GE}	- Offline tests, incl. double pulse tests and power cycling tests - Monitoring V_{CE} - Monitoring I_{leak} - Monitoring V_{GE} or gate charging - Monitoring T_j or R_{th} - Data-based indirect approaches
Capacitors [47, 49, 50]	- E-Caps: $C/C_0 < 80\%$, or $ESR/ESR_0 > 2$ - MPPF-Caps: $C/C_0 < 95\%$, or $\tan\delta/\tan\delta_0 > 3$, or $R_p/R_{p0} < 1.5\%$ - MLC-Caps: $R_p < 10^7\Omega$, or $C/C_0 < 90\%$, or $\tan\delta/\tan\delta_0 > 2$	- LCR meter, X-ray or other offline approaches - Obtaining C by: $C = \frac{1}{\Delta v_c} \int i_c dt$ - Obtaining ESR by: $ESR = \frac{V_{DC} - V_c}{i_c}$ - Obtaining ESR by: $ESR \propto V_c$ - Obtaining ESR by: $ESR = \frac{\Delta v_c \times R}{R \times \Delta I_L - \Delta v_c}$ - Data-based indirect approaches

Note 1: For power semiconductors, G / C / E = gate / collector / emitter; V = voltage, R = resistance, t_{on} / t_{off} = switching-on / off time, T_j = junction temperature, R_{th} = thermal resistance, V_{DC} = direct current (DC) voltage.

Note 2: For capacitors, E-Caps / MPPF-Caps / MLC-Caps = aluminum electrolytic / metallized polypropylene film / multilayer ceramic capacitors; C = capacitance,

ESR = equivalent series resistance, $\tan\delta$ = dissipation factor, R_p = insulation resistance, i_c / I_L = capacitor ripple current stress, v_c = capacitor voltage stress.

3.7 PARAMETERS FOR EVALUATING NEW POWER ELECTRONICS

Power electronic components in NPPs may reach end-of-life status and cease production, largely due to advancements in semiconductor technologies and design standards. For example, silicon-based IGBTs and diodes widely used in converter circuits for excitation systems or UPS devices can be replaced by newer IGBTs and alternative materials like SiC and GaN. These newer technologies offer higher power densities, improved thermal management, and greater efficiency, making them capable of operating in more demanding environments, though most NPP applications, such as auxiliary systems, typically operate under low-load and relatively mild conditions.

Similarly, control rectifiers once based on older thyristor technology can be shifted toward modern IGBT or SiC-based rectifiers, which provide faster switching capabilities and reduce harmonic distortion. The increased use of digital controllers and condition-monitoring systems also marks a significant difference in the design and operational effectiveness of modern power electronics in NPPs, which can better withstand the challenging environmental conditions and frequent load variations.

When selecting replacements for obsolete power electronics, several parameters are crucial to consider:

- **Thermal Management:** As thermal loading directly impacts the reliability and lifespan of components, robust thermal management systems are essential. SiC and GaN devices, which inherently handle higher temperatures better than traditional silicon, can extend lifespan and performance.
- **Control and Controllability:** The flexibility in control options, whether the device is controllable, semi-controllable, or uncontrolled, dictates operational reliability and robustness. The ability to integrate with NPP control systems and adjust based on grid and load conditions is highly beneficial, as it ensures seamless coordination with safety mechanisms, enhances fault tolerance, and enables dynamic response to operational changes. This adaptability contributes to improved system stability, reducing the risk of unexpected failures and allowing for optimized energy distribution within the NPP infrastructure.
- **Maintenance and Monitoring:** Considering ease of maintenance and the capability for real-time monitoring is essential to ensure the longevity and reliability of the equipment. Modern devices often come equipped with integrated condition-monitoring sensors to identify signs of degradation early.
- **Electrical Properties:** Based on EMC standards (EN/IEC), electrical properties include input characteristics, output Specifications, protection features, and environmental considerations:

- **Input characteristics:** Key factors include the input voltage range, current rating, Total Harmonic Distortion in current (THDi), and power factor. Additionally, the need for a transformer—whether external or integrated—along with input frequency (50/60 Hz) should be considered to ensure compatibility and efficiency.
- **Output specifications:** Assessment involves the output voltage range (minimum and maximum), maximum load capacity (rated power), and output voltage ripple (for DC applications). Efficiency at the rated point of operation and output frequency (for AC applications) are also crucial for matching or exceeding performance benchmarks.
- **Protection features:** Essential protection properties include the short-circuit current rating and the device's tolerance to high and normal ambient temperatures.
- **Environmental considerations:** Factors such as cooling method, IP protection degree, gross and net weight, and physical volume must be considered, as they influence the performance and durability of power electronics in various operating conditions.
- **Material Choices and Packaging:** The choice of materials (GaN, SiC) and packaging technology greatly influences device robustness, particularly in high-stress environments. For example, SiC has superior thermal conductivity and efficiency, which make it suitable for high-voltage, high-temperature applications typical in NPP environments.

Deviations in specifications or characteristics due to manufacturer variability can be significant, especially in power electronics used in NPP safety systems. These can be accounted for by:

- Utilizing IEC standards like IEC 61225 and IEC 63046 to define acceptable thresholds for deviations in component properties such as thermal performance, switching characteristics, and efficiency.
- Conducting thorough validation and compatibility tests when replacing obsolete equipment with new components from different manufacturers, ensuring they meet the operational requirements.
- Including reliability-focused metrics such as mean time between failures (MTBF) and mean time to repair (MTTR) in procurement specifications to ensure consistency across manufacturers.
- Adjusting system-level designs, such as cooling or control strategies, to accommodate variability in semiconductor performance (e.g., thermal coefficients, switching losses).
- Using historical failure and performance data from current manufacturers to assess potential risks or deviations.

3.7.1 Comparison of Current and Past Power Electronics Designs

Modern power electronics have evolved significantly over the past two decades, benefiting from advancements in materials, topologies, and protection mechanisms. Contemporary devices incorporate wide-bandgap materials like SiC and GaN, enabling higher voltage handling, faster switching, reduced losses, and improved energy efficiency under high-load and high-temperature conditions.

Beyond enhanced performance, modern power electronics designs, particularly at the component and module level, incorporate integrated protection features such as overcurrent and overvoltage protection, significantly improving fault tolerance. While robustness depends on factors like thermal management, fault protection, and component selection, newer devices offer both default and optional active and passive fault-tolerance strategies. Unlike earlier designs that primarily relied on passive protection, modern systems integrate configurable active fault-tolerant mechanisms capable of dynamically detecting and mitigating disturbances, providing an additional layer of resilience and adaptability based on application requirements.

Compared to legacy power electronics, contemporary designs incorporate advanced protection technologies that significantly enhance resilience against external disturbances. Traditional systems primarily relied on passive protection mechanisms, which could tolerate faults to a certain extent but lacked adaptive response capabilities. In contrast, modern power electronics integrate active fault-tolerant designs, which continuously monitor, detect, and dynamically respond to faults in real-time. These systems incorporate fault detection and isolation (FDI), control reconfiguration strategies, and redundancy management, ensuring minimal disruption and enhanced operational reliability in demanding environments such as nuclear power applications. Additionally, improved EMI filtering and advanced surge suppression technologies further reduce the likelihood of disturbances propagating through the system, enhancing overall robustness.

3.7.2 Quantifying Isolating Properties of Active and Passive Components

The isolating properties of equipment can be assessed by evaluating how components respond to disturbances, either upstream or downstream. Passive components like inductors, transformers, and capacitors can help isolate certain frequencies and dampen fluctuations, providing basic protection against noise and voltage spikes. Active components (e.g., IGBTs with built-in short-circuit protection) can offer more dynamic control by adjusting their behavior during disturbances. However, these active components introduce switching and conduction losses, leading to increased temperature. To ensure reliable operation and prevent thermal degradation, appropriate cooling mechanisms such as air cooling, liquid cooling, or heat sinks must be employed to manage excess heat.

The design, particularly in terms of component layout and packaging, plays a crucial role in enhancing a device's resilience to external faults and preventing disturbances from propagating downstream. Reinforced insulation within device packaging strengthens protection against voltage breakdown, while the integration of isolated gate drivers, EMI filtering, and surge suppression mechanisms ensures electrical

noise and transient faults are contained. These features help maintain stable operation, prevent cascading failures, and safeguard downstream components, particularly in high-reliability applications such as nuclear power systems.

3.7.3 Aging and Common Cause Failure (CCF)

Aging in power electronic components can increase susceptibility to CCF in NPPs, as components gradually lose their original tolerance levels and response accuracy. Over time, thermal cycling, electrical stress, and environmental factors contribute to degradation, leading to shifts in operational parameters and a higher likelihood of concurrent failures under stress. Inadequate fault separation can further exacerbate this issue, as aging effects become correlated across subsystems, weakening isolation barriers and increasing the probability of simultaneous failures. To mitigate these risks, effective fault isolation strategies, diverse component selection, and robust thermal management are essential in ensuring long-term system reliability.

While modern digital control and protection systems provide enhanced monitoring, diagnostics, and operational flexibility, their implementation in NPPs introduces additional challenges. The qualification of software-based protection systems demands extensive verification and validation, often requiring compliance with stringent industry standards such as IEC 61513 and IEC 63046. This process can significantly extend development timelines and increase costs. In some cases, regulatory constraints may even prevent the use of digital solutions in certain safety-critical applications, making conventional analog systems a more viable alternative.

Furthermore, digital systems introduce concerns related to cybersecurity, software vulnerabilities, and long-term maintenance, as periodic software updates and patches must comply with strict validation procedures. Given these factors, careful evaluation of qualification requirements is essential when considering digitalization in NPP auxiliary systems. Operators must balance the benefits of advanced digital control with the complexities of compliance, ensuring that new systems meet both safety and operational requirements.

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4 Manufacturer Input and Technological Solutions

4.1 OVERVIEW OF AVAILABLE TECHNOLOGIES

Reputed manufacturers provide a range of technologies for power electronics in NPP applications. Current solutions include traditional silicon-based semiconductors, such as thyristors and IGBTs, which are commonly used in UPS systems, rectifiers, and inverters. For example, AC/DC converters using 6-pulse or 12-pulse thyristor bridges, along with IGBT-based inverter bridges, are prevalent across critical safety and operational systems in NPPs.

Emerging technologies such as SiC and GaN modules are gaining attention for their potential advantages in high-efficiency and high-temperature applications. These modules offer reduced losses and the enhanced thermal performance, making them suitable for environments requiring high reliability and compact designs. However, their application in NPPs remains exploratory, with ongoing research into their long-term reliability under operational stresses.

Manufacturers also emphasize robust design considerations, such as incorporating temperature and current sensors, to enhance system monitoring and protection against overvoltage, overheating, and transients. Advanced cooling techniques, modular designs, and redundancy strategies further contribute to ensuring operational safety in these systems.

4.2 KEY FEATURES OF AVAILABLE SOLUTIONS

Available solutions from manufacturers exhibit several key features tailored for reliability and safety in NPP environments. These include:

1. **Enhanced Fault Tolerance:** IGBT-based inverter bridges are integrated with fast-switching capabilities and overcurrent protection to manage transient conditions and overload scenarios effectively. These systems are designed to optimize performance by minimizing switching losses while ensuring system reliability during high-current events. Advanced circuit designs incorporate multiple protection mechanisms, such as current measurement and desaturation detection, to prevent damage and ensure safety:
 - **Current Measurement:** As illustrated in **Fig. 4.1 (a)**, this technique utilizes a shunt resistor within the inverter leg to measure current flow directly. A comparator is included to evaluate the current against a predefined safe threshold. If this threshold is exceeded, the controller or gate drivers swiftly respond to mitigate the risk, protecting the system from potential shoot-through and motor winding faults. Potential shoot-through faults, where simultaneous conduction of both switches in a half-bridge leads to excessive current and possible component damage, and motor winding faults, resulting from insulation breakdown causing short circuits within the motor windings, are considered in the analysis.

- **Desaturation Detection:** Shown in Fig. 4.1 (b), this method employs the IGBT itself as a sensor to detect overcurrent by monitoring the collector-emitter voltage. Under normal saturated conditions, this voltage is low (1 V to 4 V). If a short-circuit occurs, the voltage rises sharply due to the IGBT moving to its linear region, triggering the protective circuitry if the voltage reaches set threshold levels (typically 7 V to 9 V). This mechanism helps in quickly identifying and responding to fault conditions.

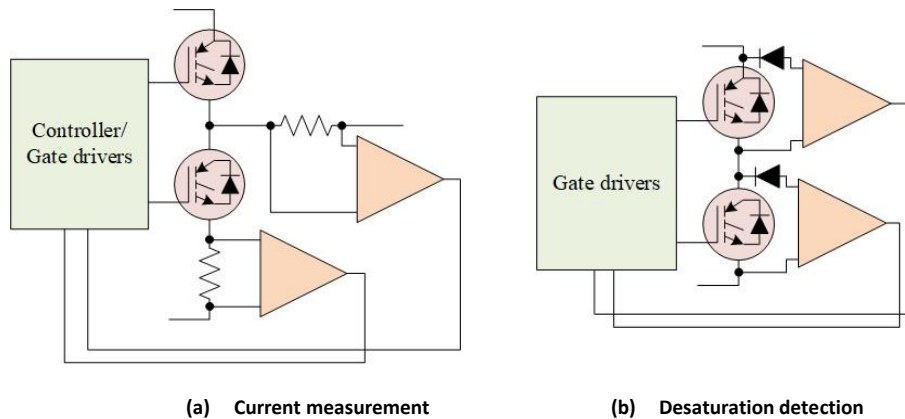


Figure 4-1 Examples of IGBT overcurrent protection techniques

Both current measurement and desaturation detection are critical for ensuring rapid response to overcurrent conditions. They enable protective actions to be initiated well within the IGBT's short-circuit +withstand time, enhancing system resilience. Additionally, gate drivers are specifically engineered to modulate the turn-off rate during overcurrent incidents. This control over the di/dt is crucial in mitigating the effects of parasitic inductance, which can lead to destructive overvoltage spikes across the IGBT. These strategic enhancements are vital for the robust fault tolerance and operational efficiency of modern high-power IGBT-based inverter bridges, making them indispensable in advanced electrical drive systems.

2. **Redundancy and Backup:** The redundancy and backup features of UPS systems are critical for ensuring continuous and reliable power delivery, especially in environments where downtime can lead to significant disruptions or losses. As demonstrated in Fig. 4.2, the integration of battery-backed inverters, maintenance bypass switches, and static bypass switches in UPS systems plays a pivotal role in achieving this reliability. Here's how each component contributes:

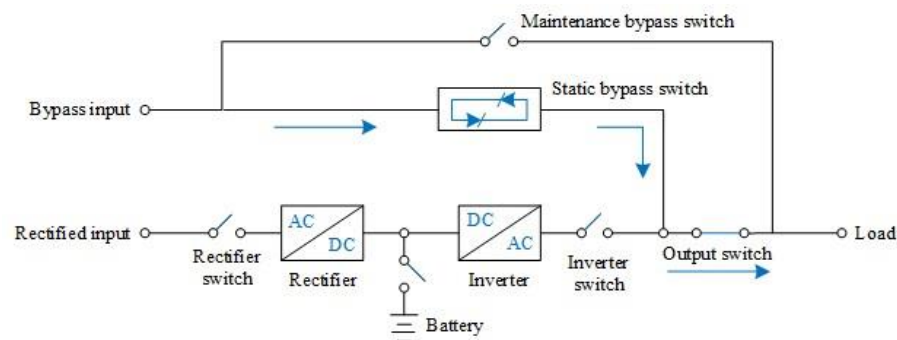
- **Battery-Backed Inverters:**

- These inverters ensure that even during power failures, the system can continue to provide uninterrupted power by converting the stored DC power from batteries into AC power for the load.
- The inverters act as a primary power source when utility power is unavailable, ensuring continuous operation without interruption.

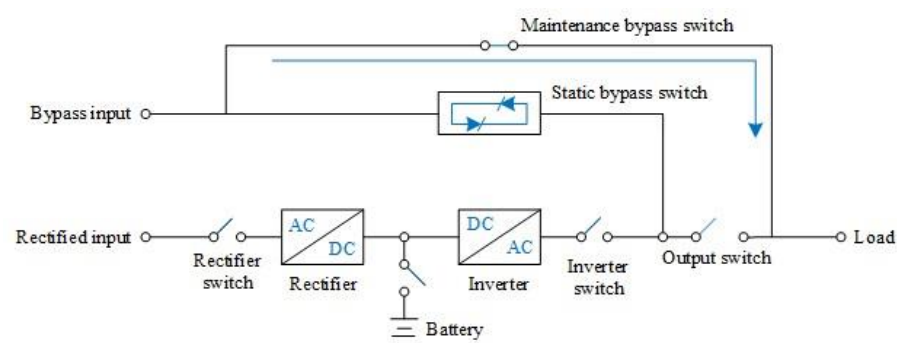
➤ **Static Bypass Switches:**

- In the event of an inverter failure or when the UPS is overloaded, static bypass switches automatically transfer the power load to the mains utility power without delay. This switch happens in less than four milliseconds, effectively ensuring that there is no perceivable interruption in the power supply.
- By instantly switching to an alternate power source, these switches allow the UPS system to maintain power availability and protect against potential downtime, provided the voltage level and stability of the alternative source are within the acceptable range.

The combination of these two features in UPS systems not only ensures seamless power delivery during disturbances but also significantly enhances the overall availability and reliability of power, crucial for critical operations. This system design, as depicted in the diagrams, provides a robust framework for managing power continuity and reducing potential downtime in various industrial and commercial settings.



(a) UPS system with activated static bypass switch



(b) UPS system with activated maintenance bypass switch

Figure 4-2 UPS systems with static and maintenance bypass switches

3. **Predictive Maintenance Support:** Predictive maintenance, especially in nuclear power plants, leverages advanced technologies to optimize maintenance processes and improve equipment reliability. By integrating real-time data analytics with predictive maintenance strategies, nuclear

facilities can significantly reduce unplanned outages, thus enhancing safety and operational efficiency.

The system achieves this by continuously monitoring equipment conditions through an array of sensors installed at strategic locations throughout the plant. These sensors collect data on key operational parameters like temperature, voltage, and current, providing a comprehensive view of equipment health in real time. This data is then processed using sophisticated algorithms that can predict potential failures before they occur. By identifying these potential issues early, the predictive maintenance system allows for timely interventions, which can be scheduled during regular maintenance periods, thereby minimizing disruptions to plant operations.

Moreover, this approach supports the maintenance teams by providing them with actionable insights derived from the data analysis. This helps in making informed decisions about when and how to perform maintenance activities, which in turn leads to a more efficient allocation of resources and extends the lifespan of the equipment. Additionally, the system's ability to learn from historical data enables continuous improvement in its predictive capabilities, making it increasingly effective over time.

In essence, the implementation of predictive maintenance systems in nuclear power plants not only helps in avoiding catastrophic failures that could lead to environmental and health hazards but also contributes to the overall sustainability of energy production by ensuring the plants operate more reliably and efficiently. This proactive maintenance strategy is crucial for meeting the high safety and reliability standards required in the nuclear industry.

The predictive maintenance framework shown in **Fig. 4.3** efficiently guides maintenance operations in a nuclear power plant by initiating real-time anomaly detection and sensor selection. Upon detecting any anomalies, the system predicts the trend of equipment condition. If this trend exceeds safe operational thresholds, an unplanned shutdown is triggered to prevent immediate risks. Otherwise, the system assesses the remaining useful life of the equipment to determine if a temporary or scheduled shutdown is necessary, allowing for timely maintenance interventions that ensure continuous safe operation and minimize unscheduled downtimes. This systematic approach leverages advanced monitoring and predictive analytics to enhance reliability and safety in plant operations.

A practical example of predictive maintenance in power electronic systems is the use of the temperature-dependent collector-emitter voltage (U_{CE}) of IGBTs as an indicator of thermal degradation. The relationship $U_{CE}=f(T_j)$, where T_j is the junction temperature, allows the estimation of internal device aging. As the IGBT undergoes repeated thermal cycles, degradation mechanisms such as solder fatigue and die-attach delamination cause an increase in U_{CE} at a given T_j . This shift serves as a non-invasive, in-situ indicator of wear-out.

In nuclear power plants, this relationship is frequently used as part of condition-based monitoring systems. By tracking the deviation of U_{CE} over time under known operating conditions, predictive algorithms can estimate the remaining useful life (RUL) of the component. This information feeds into higher-level decision logic, such as the one illustrated in **Fig. 4.3**, to determine whether an unplanned,

temporary, or scheduled shutdown is necessary. Such predictive approaches have been implemented in UPS systems and rectifier modules, enhancing system reliability while reducing the risk of unexpected failures.

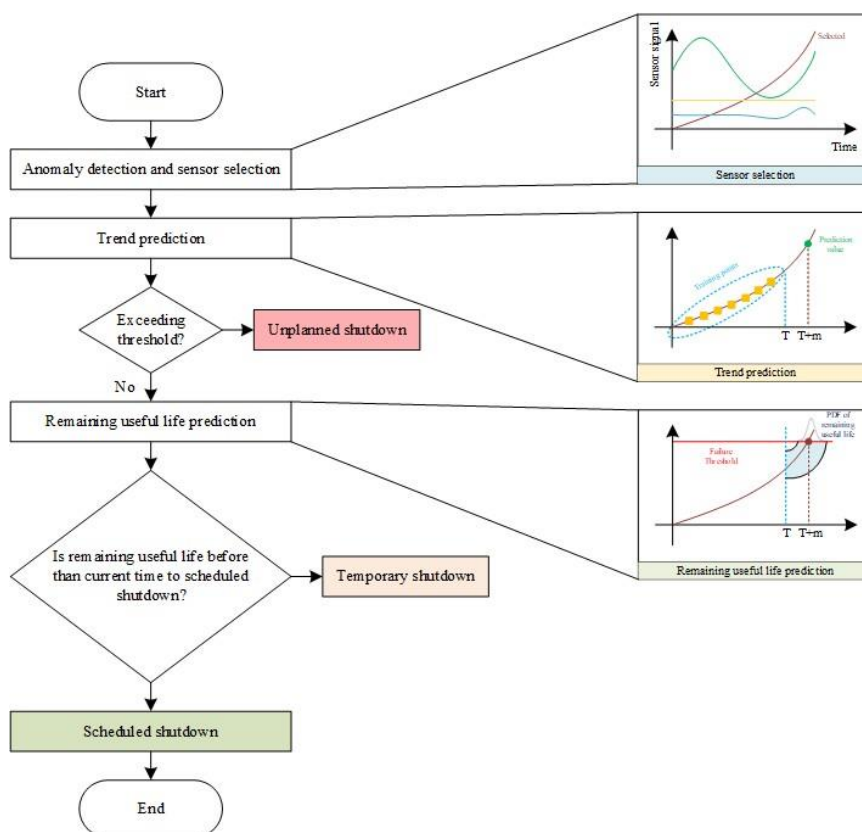


Figure 4-3 Overview of a sample predictive maintenance framework for NPPs

4. **Compatibility with Harsh Environments:** Technologies are designed to withstand environmental challenges such as thermal cycling, high humidity, and electrical transients. For example, heat sinks with embedded temperature sensors are used to maintain stable operation in variable thermal conditions.

4.3 LIMITATIONS OF CURRENT TECHNOLOGIES

While existing technologies are robust, they have certain limitations that need addressing for enhanced reliability and efficiency:

1. **Aging of Components:** Power semiconductors, particularly capacitors, are prone to wear-out failures due to thermal and electrical stress. This impacts long-term reliability and necessitates periodic replacements or maintenance.
2. **Common Cause Failure Risks:** The use of similar technologies or components from the same manufacturer across different systems increases the risk of common cause failures. This issue is particularly significant in critical applications where redundancy is essential.

3. **Limited Adoption of Emerging Technologies:** While SiC and GaN modules offer promising advantages, their deployment in NPPs is still in its infancy. Challenges related to cost, availability, and long-term reliability under harsh operational conditions need to be addressed.
4. **Dependence on Manufacturer Support:** Maintenance for some critical components, such as frequency converters, relies on periodic inspection and service reports from manufacturers. This dependency can create delays or inconsistencies in addressing operational issues.

By addressing these limitations through innovations such as advanced predictive maintenance tools, improved component materials, and diversified supplier strategies, the resilience and performance of power electronics in NPPs can be further enhanced.

4.4 DETAILED ANALYSIS OF DAMAGE OBSERVATIONS

This subsection focuses on the observed damages in the static switches of customer UPS systems, with specific references to visual evidence from the provided analysis.

4.4.1 Damage to Thyristor Modules

Several static switches exhibited significant damage, as observed in the thyristor modules analyzed. For instance:

- **Melted Area on Chip Edge:** The thyristor in module SSW1 TH2 displayed a melted area on the chip edge, indicative of overheating potentially caused by overvoltage or excessive current (**Fig. 4.4**).
- **Burnt Area Around Gate:** Module SSW2 TH2 showed a burnt region near its gate, which is likely due to a critical rate of current rise exceeding acceptable thresholds, such as $di/dt > 250 \text{ A}/\mu\text{s}$ (**Fig. 4.5**).

These failures underscore the susceptibility of thyristor modules to thermal and electrical stresses, highlighting the importance of robust protection measures.



Figure 4-4 Defective thyristor - module SSW1 TH2



Figure 4-5 Defective thyristor - module SSW2 TH2

4.4.2 Faulty Cathode Spring and Associated Melting

In module DC08162, the analysis revealed a faulty cathode spring, which was accompanied by melting of the spring and its surrounding plastic cover. This damage led to a loss of electrical contact with the cathode side of the thyristor, impairing the triggering process during electrical operation (**Figs. 4.6** and **4.7**). The melted plastic and spring deformation point to electrical overstress (EOS), likely due to transient overcurrents, possibly from lightning strikes.



Figure 4-6 Faulty cathode spring



Figure 4-7 Melted cathode spring

By examining these observations, the root causes of the failures were traced back to environmental factors like electrical transients and overvoltage conditions. These findings emphasize the need for preventive measures, such as enhanced surge protection and better cooling strategies, to mitigate similar issues in the future.

5 Nordic NPPs: Input, Recommendations, and Discussion

5.1 SUMMARY OF INTERVIEWS WITH NORDIC NUCLEAR POWER PLANTS

The interviews revealed the critical role of power electronics in ensuring the safety and reliability of NPPs. Key components such as rectifiers, UPS units, and inverter bridges face unique operational and environmental challenges. For instance:

- The **rectifier systems** include 12-pulse thyristor bridges, diode-based rectifiers, and IGBT-based inverter bridges. Their primary function is to handle transients, ensure stable power supply during abnormal events, and support critical loads such as reactor coolant pumps and control systems.
- Aging and failures are frequently observed in components like capacitors, controller boards, and semiconductors, with the **rectifier faults** often linked to issues like over-voltage or loose connections (e.g., glass tube fuse failures).
- Environmental factors such as temperature and thermal cycling have a significant impact, with **cooling systems** playing a critical role in maintaining operational stability. UPS systems include periodic maintenance to address wear and ensure functionality during transients and voltage disturbances.

5.2 KEY FINDINGS FROM THE LITERATURE STUDY

- Key finding from the literature and operational feedback:
 - **Vulnerability of Components:** The aging of electronic components such as semiconductors, capacitors, and resistors in NPPs is influenced by environmental and operational stress factors. These factors can include high temperatures, radiation, and humidity, which affect the reliability and safety of the components used in critical instrumentation within the reactor containment areas [1]. Research, primarily conducted by Sandia National Laboratories, emphasizes the specific aging mechanisms in the reactor containment area, where components are exposed to high levels of neutron and gamma irradiation over the plant's operational lifespan, typically 40 years [2]. These conditions nearly reach the radiation tolerance limits of commercial semiconductor devices, necessitating the simulation of both neutron and gamma radiation in aging studies to accurately reflect the containment environment [3]. Additionally, the assessment of surge protective devices, although not classified as safety-related, reveals their importance in minimizing risk by protecting against electrical power anomalies. Despite their critical role, these devices showed minimal risk-related failures in the past, indicating that age-related deterioration was not significant enough to prevent reactor trips or cause other initiating events [4]. This underscores the need for ongoing

investigation into dose-rate effects, radiation-voltage bias interactions in semiconductors, and the impact of environmental factors such as moisture on electronic packaging.

- **Aging Management Techniques:** Effective aging management strategies are critical in NPPs to ensure safety and reliability. This includes the use of advanced diagnostic and prognostic tools to monitor and predict the aging process of power electronics. Techniques such as Arrhenius' criterion for thermal aging and ongoing qualifications help in understanding the aging degradation curves and the effects of aging under severe conditions.

The literature on semiconductor aging offers a diverse range of innovative methods to assess and enhance the performance and longevity of these critical components. Advanced online monitoring techniques for IGBTs using temperature-independent electrical aging indicators allow for improved sensitivity and ease of implementation [5]. The introduction of silver interlayers in power semiconductor packaging effectively mitigates thermal aging, demonstrating significant durability under high-temperature conditions [6]. Efficient testing methods that focus on median degradation rather than traditional metrics streamline the aging process, providing more accurate and cost-effective solutions [7]. Enhancements in photodiodes through the formation of silicon suboxide layers illustrate how aging can positively affect device capabilities [8]. Non-destructive electromagnetic monitoring and acoustic emission techniques provide new ways to track aging without damaging the devices, offering a promising avenue for improved health monitoring and early detection of aging effects [9, 10]. The exploration of bond-wire resistance as an indicator and the characterization of metallization aging through non-contact eddy current techniques underscore the shift towards more sensitive and practical monitoring solutions [11, 12]. The study of mutual and self-aging effects in power converters highlights the critical impact of aging on device thermal behavior and lifespan [13]. Lastly, the strategic planning of aging experiments using assurance test matrices helps in optimizing test allocations, facilitating a comprehensive understanding of long-term semiconductor device performance and failure rates [14]. These approaches illustrate a significant evolution in aging monitoring and mitigation techniques, enhancing the reliability and safety of semiconductor modules in various applications.

- **Environmental Controls:** Maintaining stringent environmental controls is essential to mitigate the aging effects. Cooling and humidity control systems play a vital role in ensuring the long-term reliability of power electronics by providing stable operating conditions that reduce the risk of accelerated aging. Environmental controls in nuclear power plants are crucial for safeguarding both the environment and public health. These controls involve rigorous safety protocols and continuous monitoring to manage and mitigate the risks associated with nuclear energy production. The aim is to prevent accidents that could lead to radioactive releases, which would have severe and long-lasting impacts on the surrounding environment. Additionally, these controls are subject to stringent regulatory standards, which evolve based on past

experiences and technological advancements to ensure that safety measures are up to date and effective. Effective environmental control systems in nuclear facilities are pivotal in maintaining public trust and ensuring the sustainable use of nuclear power as a significant energy source [15].

- **Software and Hardware Integration:** Aging management is not limited to hardware components but also extends to software systems. Software aging management in nuclear power plants is critical for ensuring the safety and reliability of digital control systems. It involves proactive strategies from the design phase through maintenance, employing fault-avoidance and fault-tolerance technologies, along with rigorous testing and validation to address potential software degradations. Continuous monitoring and predictive analytics are crucial for detecting aging signs early and implementing timely interventions, thus maintaining the operational integrity of nuclear power systems and adhering to stringent safety standards [16].
- **Predictive Maintenance and Monitoring:** Adopting predictive maintenance strategies using modern monitoring techniques such as electromagnetic monitoring and acoustic emission can significantly enhance the ability to detect early signs of aging in electronic components and systems. These techniques facilitate non-invasive monitoring, which is critical for continuous operation without interruptions. Predictive maintenance in nuclear power plants, represents a sophisticated integration of advanced monitoring technologies and reliability-centered maintenance strategies. This approach emphasizes condition-based maintenance to preemptively address equipment issues before they lead to failures, thereby enhancing both safety and operational efficiency. Utilizing online monitoring systems and diagnostics tools, such as vibration analysis and thermal imaging, predictive maintenance enables the detection of potential problems during the early stages of equipment degradation [17]. This proactive strategy significantly reduces unplanned downtime and maintenance costs, while simultaneously extending the operational life of critical systems and components, ensuring that nuclear facilities operate safely and reliably within their economic constraints.

5.3 EXPERIENCES AND REQUIREMENTS OF NPPS

Based on the operational insights:

- **Functional Requirements:** Power electronic systems must handle load cycling, ensure fault isolation, and maintain stable operations during grid disturbances. For example, an emergency power supply busbar distributes power to safety related loads even during power interruptions, emphasizing the importance of battery backup systems.
- **Operational Challenges:** Failures due to wear-out or single-event issues, such as over-current and over-voltage, have highlighted the need for robust design and advanced monitoring. Components such as capacitors and semiconductors need regular inspections and eventual replacement.
- **Environmental Adaptation:** Effective cooling and environmental control are essential to mitigate the impact of harsh operational conditions, such as temperature variations and thermal cycling.

5.4 RECOMMENDATIONS FOR FUTURE TECHNOLOGY ADOPTION IN NPPS

This section builds upon the findings presented in the earlier Energiforsk report, *“Ageing of Power Electronics in NPP Safety Systems,”* which concluded that many auxiliary power systems in Nordic NPPs operate under relatively mild environmental conditions and low load levels. That report identified obsolescence and challenges with spare parts availability as primary motivations for replacement, rather than failure due to environmental stress. Building on those insights, this report focuses on strategic approaches for adopting modern power electronics (e.g., IGBT-based solutions) in these environments while ensuring compliance with reliability and safety requirements. The gradual transition strategies proposed here aim to preserve system robustness while accommodating evolving technologies.

This subsection details the implementation strategies and expected outcomes of the proposed recommendations, providing a roadmap for technological advancements in NPPs. IGBTs offer higher efficiency and superior power quality compared to thyristors; however, they are less robust and have lower inherent reliability. In NPP applications, reliability and safety are paramount. Therefore, to integrate IGBT technology in this field, it is crucial to implement measures that enhance its reliability. Furthermore, the existing converters were not originally designed for NPP applications, necessitating a carefully planned, gradual transition to ensure system stability and operational security.

Thyristor-based converters are known for their robustness and long operational history, but they suffer from lower efficiency and higher harmonic distortions, which negatively impact power quality. On the other hand, IGBT-based converters provide higher efficiency and improved power quality but require additional reliability enhancements to match the robustness of thyristors.

To compensate for the lower robustness of IGBT-based converters, several strategies should be implemented:

1. Thermal Management Solutions:

Both passive and active thermal management techniques are essential for maintaining safe operating temperatures in IGBT-based converters. These techniques help prevent thermal damage, improve reliability, and ensure the longevity of the system. Passive methods, such as convection cooling and improved ventilation, rely on natural airflow and the dissipation of heat through surface area, making them effective for low-power systems. However, for high-power applications, these methods may not be sufficient due to the increased heat generation. To address this, active cooling methods like liquid cooling and forced air cooling are employed. Liquid cooling provides superior heat transfer capabilities, making it ideal for high-power systems, while forced air cooling further enhances heat dissipation. This combination allows for precise control of temperature, reducing the risk of thermal damage and ensuring the stability and performance of IGBT-based converters under demanding conditions.

Thermal Damage Distribution Among Converters: Beyond local cooling solutions, active thermal management also involves distributing heat loads across converters to prevent overheating in any single unit. By strategically balancing the thermal load among converters, it's possible to avoid thermal hotspots and improve overall system reliability. This can be achieved through thermal sensing and load balancing, ensuring that units with lower thermal loads are not overburdened, while higher loads are directed toward converters with more advanced cooling solutions.

2. Real-Time Monitoring and Diagnostics:

Predictive maintenance tools, including thermal sensors and condition monitoring systems, can proactively detect and mitigate potential failures. Diagnostic systems play a critical role in fault detection and system health monitoring. Fault detection techniques should be integrated into the operational strategy to ensure early identification of any issues. However, condition monitoring and fault detection should be gradually integrated into the system. Initially, the focus should be on equipping the converters with diagnostic tools, but actions should not be taken immediately based on the data. Instead, the first phase should be focused on observing, learning, and testing the system's behavior over time. This observational period should last for 2–3 years, during which the system's reliability, performance, and fault patterns will be assessed. Diagnostic tools, including thermal sensors, voltage sensors, and vibration monitoring, will continuously collect data to identify potential issues. After this period of data collection, the patterns will help inform operational adjustments and guide future maintenance strategies.

3. Redundancy Redesign and Gradual Replacement:

The current thyristor-based converters operate at only 25% utilization with built-in redundancy. To ensure the reliability of IGBT-based converters, the redundancy strategy must be redesigned to accommodate their specific characteristics. A gradual replacement approach is recommended to minimize operational risks. The first step should be to replace one unit with an IGBT-based converter and conduct a field test over a 2–3 year period. During this time, its performance, reliability, thermal behavior, and overall system stability should be carefully monitored under real-world conditions. This gradual adaptation will allow for the collection of valuable data without compromising the plant's operational security. Based on the field test

results, necessary design modifications and improvements should be implemented. Once stability and performance benchmarks are achieved, the remaining thyristor-based converters can be gradually replaced with IGBT-based systems, ensuring a safe and reliable transition.

The integration of IGBT-based converters alongside existing thyristor-based converters may introduce system stability issues due to differences in dynamic characteristics. To mitigate these risks, a comprehensive dynamic stability analysis must be performed before and during the transition. This analysis should evaluate the interaction between thyristor and IGBT-based converters, transient response characteristics, and potential oscillations affecting power quality.

4. System Redesign for Higher DC Link Voltage:

IGBT technology brings flexibility to system design, allowing for the consideration of higher DC link voltage. This redesign option is particularly important in terms of increasing system efficiency. With IGBT-based converters, higher DC link voltages (e.g., moving to 2 kV or higher) can be implemented to reduce current levels, minimizing power losses and improving overall efficiency. A higher voltage DC link can reduce the size and cost of the system's components, such as transformers and cables, further increasing system performance and reducing operational costs. Additionally, optimizing the system for higher voltages can enhance the efficiency of power conversion, allowing for more effective use of the available power and reducing the overall energy losses across the system. This flexibility in redesigning the DC link voltage offers substantial improvements in power quality, cost savings, and system reliability when transitioning from thyristor-based to IGBT-based converters.

5. Revisit Standard Requirements for IGBTs with Extra Testing Under Relevant Conditions:

As part of the integration process, it is essential to revisit the existing standard requirements for power converters and assess them in the context of IGBT technology. This will involve carefully comparing each standard with the capabilities and characteristics of IGBT-based systems and identifying areas where the standards may need to be updated. Some existing requirements may need to be relaxed due to the improved performance of IGBTs in certain areas, such as efficiency, switching speed, and power quality. Conversely, new requirements may emerge that reflect the operational differences between thyristor and IGBT technology, especially regarding reliability, fault tolerance, and thermal management.

Furthermore, the analyses presented in Chapters 3 and 4 regarding design strategies, fault tolerance, external disturbance mitigation, and component modernization align closely with the international standards reviewed in Chapter 2. The principles emphasized in IEC 62855 (electrical system robustness), IEC 63046 (system architecture and defense-in-depth), and IEC 61225 (performance of static UPS systems) are reflected in the report's recommendations. For example, the use of redundancy, real-time monitoring, and robust component design directly support the resilience and safety mandates outlined in these standards. This alignment ensures that the proposed strategies not only improve technical reliability but also

support compliance with current international safety requirements for nuclear power systems.

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6 Conclusion

6.1 SUMMARY OF FINDINGS

This study underscores the critical role of power electronics in maintaining the safety and operational efficiency of NPPs. Through comprehensive research, including a review of national and international standards, state-of-the-art technological solutions, and feedback from Nordic NPPs, the following key insights were identified:

- Current power electronics, such as thyristor-based rectifiers and DC/DC converters, face challenges due to aging and obsolescence. Their replacement requires careful consideration of robustness, reliability, and compliance with modern safety standards.
- IGBTs and advanced converter topologies, such as DAB and modular multilevel converters, offer significant improvements in efficiency but face reliability and robustness issues, limiting their interest.
- Redesigning the system with adopting IGBT technology, including redundant design, condition monitoring, fault tolerant structures, system specifications like higher DC link voltage, and revisiting standard recommendations for new requirements for IGBT based converters could facilitate exchange of converters.
- It is highly recommended that the transition to be performed gradually within 2-3 years and careful observation for redundant operation and condition monitoring with IGBT technology can help better understanding exchange process as well as maintain reliability within transition.
- Gradual adoption of IGBT converters alongside existing thyristor-based systems requires careful dynamic modeling and stability analysis to ensure compatibility and avoid adverse interactions during the transition phase.

6.2 FINAL THOUGHTS AND NEXT STEPS

In summary, to move forward effectively, we would suggest the following actions as next steps:

1. Technical Upgrades and Standardization:

- Transition to new-generation power semiconductor technologies and power electronics converters for higher efficiency and thermal tolerance.
- Adopting modular and standardized systems to facilitate easier upgrades and replacements.
- Incorporating reliability evaluation and maintenance scheduling into system implementation.

2. Research and Developments:

- Conducting further studies on the potential and long-term impact of advanced materials / components NPP applications.
- Investigating mitigation strategies for common-cause failures and robust operational strategies with improved fault tolerance.
- Exploring advanced technologies for predictive maintenance including IoT-enabled sensors and machine learning approaches.

3. Collaborative Efforts:

- Engaging with manufacturers to ensure the availability of targeted components / techniques and acquire statistical data to comprehensively understand the technical pros and cons.

Aligning with up-to-date international standards for secure and reliable operation for seamless integration with modern power grids and requirements on operational resilience.

Overall, the findings of this project are in agreement with the international standards discussed in Chapter 2. The strategies proposed for fault-tolerant design, component replacement, and system-level protection measures are consistent with the safety and reliability principles defined in IEC 62855, IEC 63046, and IEC 61225. This alignment reinforces the relevance and applicability of the results for future upgrades in Nordic NPPs and ensures that any transition to modern power electronic solutions remains within the boundaries of internationally recognized safety frameworks.

EXCHANGE STRATEGIES FOR POWER ELECTRONICS IN RECTIFIERS AND UPS SYSTEM FOR NPP

Replacing outdated power electronics in NPP auxiliary systems is crucial for maintaining operational reliability and safety. This report highlights the benefits of integrating wide-bandgap semiconductors (SiC and GaN) and state-of-the-art DC/DC and DC/AC converter technologies to improve efficiency, thermal resilience, and regulatory compliance. It provides strategic recommendations for component selection, fault tolerance mechanisms, and real-time condition monitoring to enhance long-term system stability. The insights presented offer a practical framework for Nordic NPPs to implement future-proof solutions that align with evolving safety and performance standards.

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