AGEING OF POWER ELECTRONICS IN NPP SAFETY SYSTEMS INCLUDING RECTIFIERS AND UPS SYSTEMS

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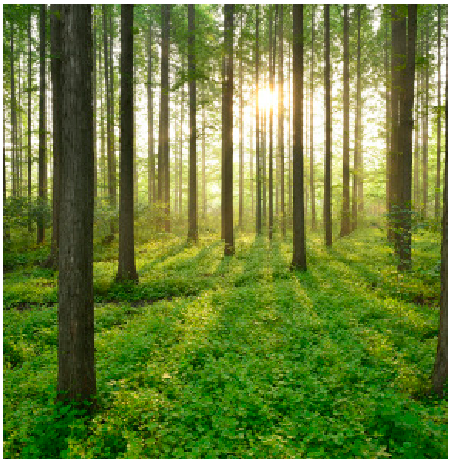
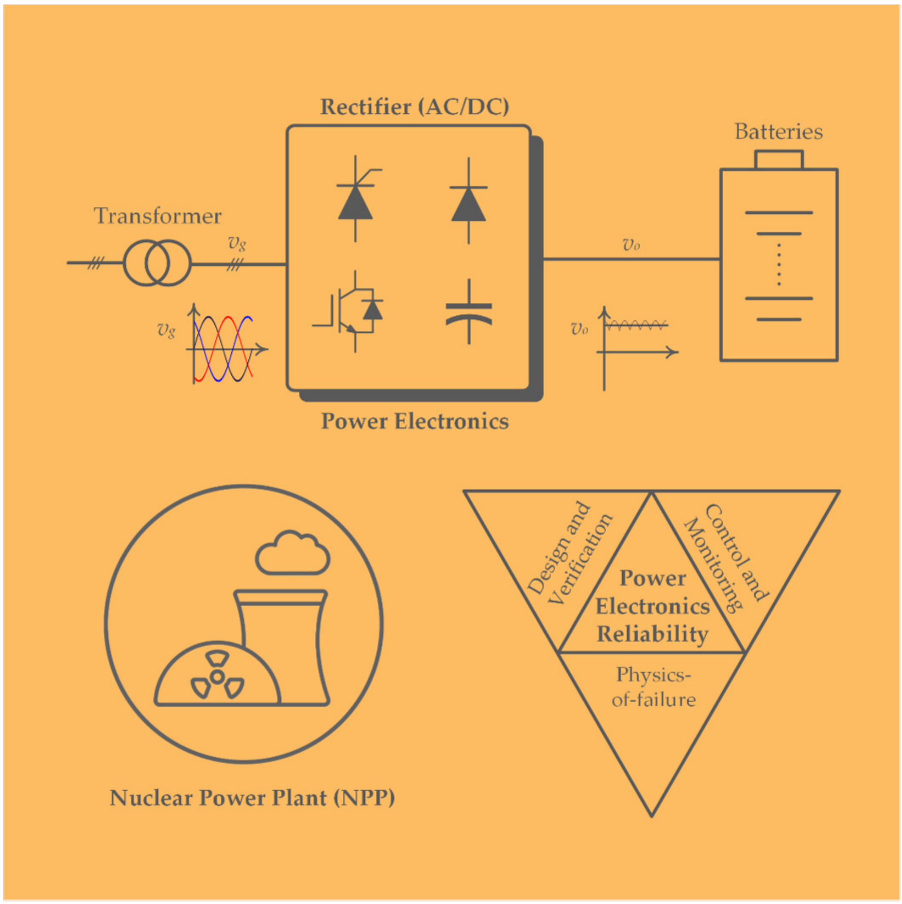


PÅVERKAN AV YTTRE NÄT IN I KÄRNKRAFTSANLÄGGNINGAR, GINO



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Content

AGEING OF POWER ELECTRONICS IN NPP SAFETY SYSTEMS INCLUDING RECTIFIERS AND UPS SYSTEMS

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Foreword

Understanding ageing and degradation of safety system equipment containing power electronics is of great interest for nuclear power plants. The ageing status might impact or be the reason for sudden failure when components are hit by a transient.

This project addresses ageing and robustness of nuclear power plant auxiliary power DC systems and UPS devices containing power electronic components. By increasing the understanding one can find better ways to monitor and predict when equipment should be replaced based on time and experienced abnormal stress.

Lessons from other industries on robustness and ageing of power electronic components are analyzed in the specific context of a nuclear power plant. Another important aspect is to understand the stressors that affect the ageing, e.g. transients from the connecting grid.

The study was carried out by Solvina and Aalborg University, with Marie-Louise Axenborg, Solvian as the project manager. The GINO programme is a part of the Energiforsk nuclear portfolio, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi. GINO has additional funding from SSM and SVK.

Summary

Ageing of power electronics impacts the reliability of systems in a nuclear power plant (NPP) and is one aspect to consider when planning for equipment maintenance as well as when planning for complete system exchange. In this report, we elaborate on ageing of power electronics specifically in the rectifiers of the NPP safety battery backup systems. Conclusions regarding the most relevant ageing mechanisms in the NPP context in relation to system reliability are provided. Also, ideas are suggested for how aspects impacting ageing can be further investigated by performing measurements on transients hitting the power electronic components and to evaluate the possible benefits with introducing condition monitoring of electronic components.

In an NPP, there are several systems and equipment containing power electronics. Power electronic components are used in generator excitation systems, in rotating diode bridges and in static excitation systems but also auxiliary power DC systems and Uninterruptable Power Supply (UPS) devices, which are essential for the plant safety. These safety systems utilize power electronic components for rectifiers, DC/DC converters, and inverters. The functionality, reliability and robustness of these systems and components need to be assured at all times.

Aspects on ageing and reliability of power electronic components are available in literature mainly from applications such as renewable energy systems and industrial motor drives and can be relevant also for power electronics in the NPP context. The report provides a general overview of ageing of power electronics based on data and experiences from e.g. wind and solar applications. Different aspects impacting ageing of power electronics are then evaluated in the Nordic NPP context. It is concluded that the main aspect impacting ageing in the NPPs are impacts from the electrical grid. Different topologies of the rectifier system (e.g. thyristor-based vs transistor-based) have different characteristics and ability to withstand impact from surge voltage and voltage amplitude variations. Transistor-based rectifier achieves better operation performance (e.g. lower output voltage ripple and higher power factor), which leads to lower ripple current and less degradation of the batteries to be charged. Nevertheless, the thyristor-based rectifier has higher over-current capability from the power semiconductor perspective.

Based on literature studies, interviews and case studies conducted during the project, the following recommendations are given: To better understand how grid transients impacts on power electronics degradation in the rectifiers, it may be appropriate to collect and map representative voltage and current data as basis for further analysis. It is important to ensure sufficient performance of protective equipment (varistors) so that the rectifier has adequate protection against existing transients from external grid. It may be worthwhile to further investigate the possibilities for and possible benefits of using condition-based maintenance to a greater extent as a complement to current routine-based maintenance. Finally, it is proposed to investigate a new redundancy strategy by increasing the number of

rectifiers with lower power. The idea is to let the power converter operate close to the rated power for higher efficiency.

Keywords

Ageing; power electronics; grid voltage variation; thyristor; transistor; rectifier; condition monitoring; redundancy

Åldring; kraftelektronik; variationer i nätspänningen, likriktare, tillståndsövervakning; redundans

Sammanfattning

Åldring av kraftelektronik påverkar tillförlitligheten hos system i ett kärnkraftverk och är en aspekt att ta hänsyn till vid planering av underhåll på utrustning och vid systemutbyten. I denhär rapporten undersöker vi åldring av kraftelektronik specifikt i likriktare för kärnkraftverkets säkerhetssystem för batteribackup. Slutsatser om vilka åldringsmekanismer som påverkar tillförlitligheten och är mest relevanta i kärnkraftverkets kontext presenteras. Vidare föreslås idéer för hur aspekter som påverkar åldring kan undersökas vidare genom att utföra mätningar på transienter som faktiskt träffar utrustningen och att utvärdera fördelarna med att införa tillståndsövervakning hos vissa elektroniska komponenter.

I ett kärnkraftverk finns flera system och utrustning som innehåller kraftelektronik. Kraftelektroniska komponenter används i generatorns magnetiseringssystem, i roterande diodbryggor och i statiska matare, men också i hjälpkraftsystem (DC) och UPS-enheter (Uninterruptable Power Supply), som är väsentliga för anläggningens säkerhet. Dessa säkerhetssystem använder kraftelektroniska komponenter för likriktare, DC/DC-omvandlare och växelriktare. Funktionaliteten, tillförlitligheten och robustheten hos dessa system och komponenter måste alltid vara säkerställda.

Information om åldring och tillförlitlighet hos kraftelektronikkomponenter finns i litteraturen huvudsakligen från applikationer inom förnybara energisystem och industriella drivsystem men kan vara relevanta även för kraftelektronik i kärnkraftverk. Rapporten ger en allmän översikt över åldring av kraftelektronik baserat på data och erfarenheter från bl.a. vind- och solenergiapplikationer. Olika aspekter som påverkar åldrandet av kraftelektronik utvärderas i rapporten utifrån de nordiska kärnkraftverkens miljö och förutsättningar och leder fram till slutsatsen att den huvudsakliga aspekten som påverkar åldring av kraftelektronik i kärnkraftverken är påverkan från elnätet. Olika topologier för likriktarsystemet (t.ex. tyristorbaserat vs transistorbaserat) har olika egenskaper och förmåga att motstå påverkan från överspänning och variationer i spänningsamplitud. Transistorbaserade likriktare uppnår bättre driftsprestanda (t.ex. lägre utspänningsrippel och högre effektfaktor), vilket leder till lägre rippelström och mindre försämring av batterierna som ska laddas. Tyristorbaserade likriktare, å andra sidan, har högre överströmskapacitet ur effekthalvledarperspektivet.

Baserat på relaterade litteraturstudier, intervjuer och fallstudier som genomförts under projektet, ges följande rekommendationer: För att bättre förstå hur transienter påverkar kraftelektroniken i likriktarna kan det vara lämpligt att kartlägga spänningstoppar och transienter från elnätet. Det är också viktigt att säkerställa tillräcklig prestanda hos skyddsutrustning (varistorer) så att likriktaren har ett tillräckligt skydd mot förekommande transienter från yttre nät. Det kan vara värt att vidare undersöka möjligheterna för och eventuella vinster med att använda tillståndsbaserat underhåll i större utsträckning som komplement till nuvarande rutinunderhåll. Det föreslås också att undersöka en ny redundansstrategi genom att öka antalet likriktare med lägre effekt med avsikten att låta effektomvandlaren arbeta nära märkeffekten för högre effektivitet.

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1 Introduction

1.1 BACKGROUND

Power electronics is one of the most important key enabling technologies in changing society from a fossil fuel-based society to a much more sustainable one. More than 70% of all electricity is processed through power electronics, thus it is crucial to design more reliable and more efficient power electronic systems for use in power generation, distribution, and consumption.

In an NPP, the functionality and reliability of auxiliary power DC systems and Uninterruptable Power Supply (UPS) devices are essential and necessary for plant safety. These safety systems utilize power electronic components for rectifiers, DC/DC converters, and inverters. In addition, power electronic components are used in generator excitation systems, in rotating diode bridges and in static converters. Since more and more power electronics are introduced in NPPs, it is of importance to guarantee system reliability. The deterioration of the power electronics might also bring a negative impact on the surrounding systems.

Aspects on ageing and reliability of power electronic components are available in literature mainly from applications such as renewable energy systems and industrial motor drives and can be relevant also for power electronic converters in the NPP context.

1.2 SCOPE

The scope of this study is to compile information about general ageing mechanisms for power electronics in different power industrial applications and relevant for main power electronic components installed in NPP auxiliary power DC systems and Uninterruptable Power Supply (UPS) systems. Furthermore, the scope was to perform analyses to conclude on ageing mechanisms relevant for the NPP power converter safety systems and to provide recommendations for health monitoring and exchange strategy for the power electronic converter systems in whole or part.

1.3 METHOD

1.3.1 Literature study

Literature studies and compilation of general knowledge base regarding ageing mechanisms, failure experiences and general methods for predicting the lifetime of power electronics were compiled. The information was mainly based on experiences in photovoltaic (PV) and wind power applications, where comprehensive data is available.

1.3.2 Interviews

Interviews were performed with representatives from the Swedish and Finnish NPPs to gain information about the power electronic components in rectifier systems in the nuclear application. Interviews were held in video meetings with representatives from one plant at a time and individuals with relevant competence for the rectifier systems (e.g. system owners, maintenance engineers) were invited. A questionnaire was sent out in preparation for the meeting.

1.3.3 Analysis

Analyses were performed based on the general knowledge base regarding ageing of power electronics and taking into account the specific conditions and system implementation in the nuclear application.

Two main types of rectifier technology, thyristor- and transistor-based, were compared to sensitivity to over-voltage and to characteristics at increased asymmetric grid conditions and the resulting impact on the battery charging.

Analysis was performed to address specific issues raised in the project mid-way meeting including grid variation impact, redundancy impact on system reliability and monitoring of rectifier systems. Ageing as a common cause for failures has not been further analysed in the report due to lack of experience and data from other applications.

The analysis results were not validated against historic data from NPPs or against experienced disturbances found in literature as such data are not or only sparsely available.

2 Power electronics in NPP safety systems

2.1 CONFIGURATION OF THE NPP POWER SYSTEM

According to the International Atomic Energy Agency (IAEA) safety standards, a typical configuration of electrical power supplies for an NPP is presented in Figure 1. Through the unit transformer and switchyard, the power generated from the main generator is transferred into the transmission lines. For the nuclear power application, the local loads from the safety bus are required to be satisfied with a high priority.

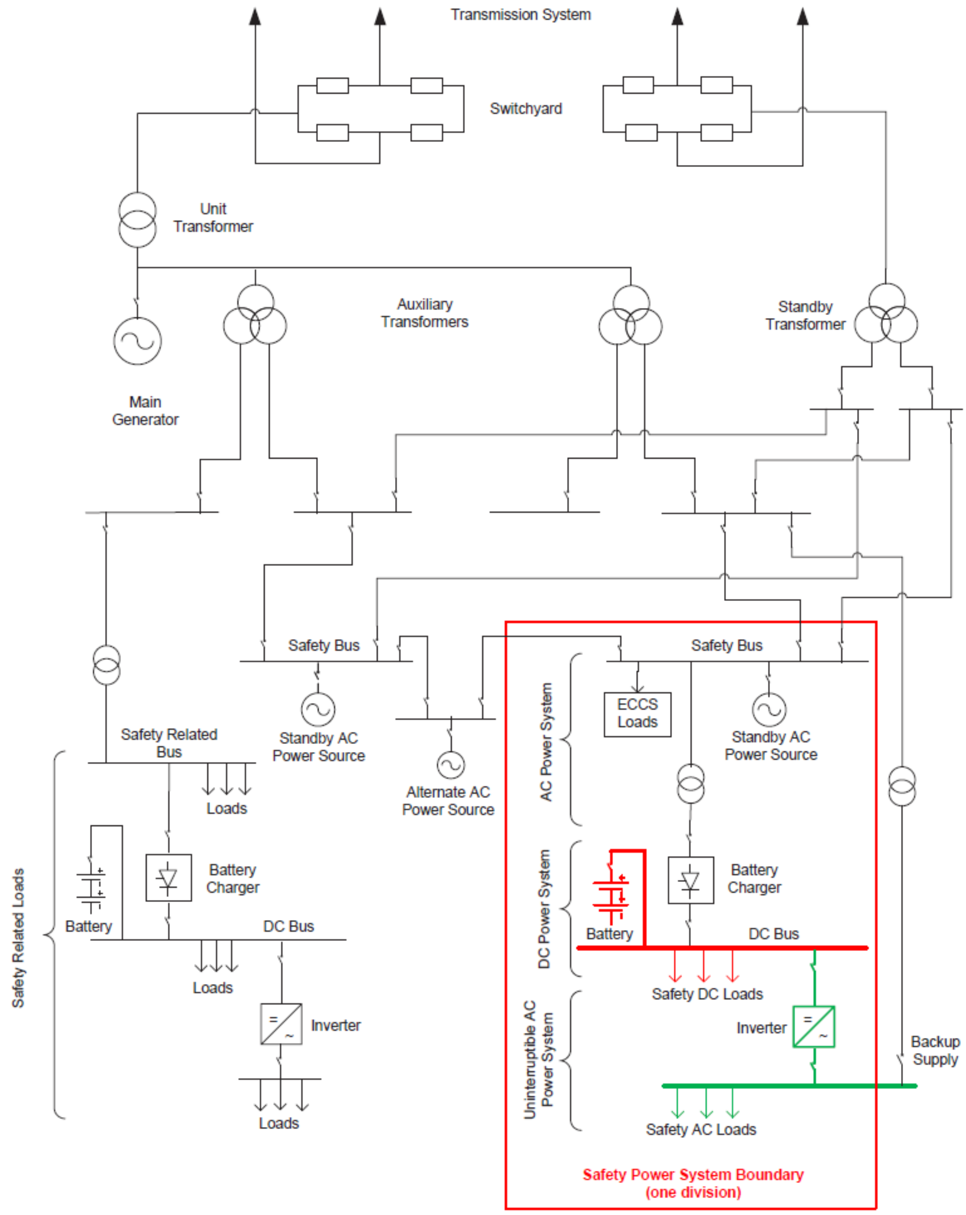


Figure 1 Schematic representation of electrical power supplies for an NPP [1]. (Note: AC – Alternating Current; DC – Direct Current; ECCS: Emerging Core Cooling System.)

There are two major subsystems of the plant power system that can support the safety bus: the off-site power system and the on-site power system. The off-site power system is comprised of the transmission system and the switchyard connecting the plant with the grid. The plant power system will provide AC power to the plant in all operation modes. The off-site power system performs an essential role in supplying the safety bus with reliable power via the auxiliary transformer or standby transformer.

The boundary between the off-site and on-site power systems is generally at the grid side of the transformer that connects to the transmission voltage. The on-site power system is composed of distribution systems and power supplies within the plant. It includes the AC and DC power supplies necessary to bring the plant to a controlled state during accident conditions until off-site power supplies can be restored. The major components of the on-site power system include the main generator, auxiliary transformer, standby AC power source, diesel generator, battery charger (rectifier), battery, inverter (uninterruptable power supply) and switching gears. The safety bus is secured with several reliable power supplies. In the case of normal operation, the power supply is provided from the transmission system and the generator. The standby AC power source, and diesel generator take over during grid outages. Some safety systems, such as Emergency Core Cooling System (ECCS), tolerate short power interruptions and are powered directly from the safety bus, while others (such as the Reactor Protection System (RPS)) require continuous power supplies and are powered by battery systems.

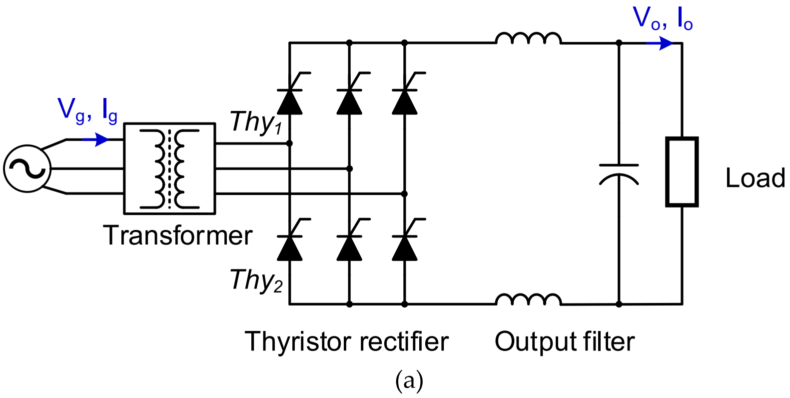
The power electronics in focus for this report are in the rectifier. The general requirement for the rectifier is to feed the connected loads and charge the battery with good quality (e.g. fulfil the voltage level, ripple, and dips). Moreover, the rectifier shall protect the system and equipment downstream, including critical inverters that may be particularly sensitive to harmful transients.

2.2 SYSTEM IN FOCUS OF THE STUDY

According to feedback from the NPP owners, the rectifiers may have various specifications in terms of the input voltage levels (e. g. 220 Vac, 400 Vac, 500 Vac) and output voltage levels (e.g. 220 V, 110 V, ±24 V). The representing topology of the applied rectifiers can be categorized into the thyristor-based and transistor-based rectifiers as shown in Figure 2 [2], [3].

For the thyristor-based rectifier, the output voltage of the thyristor rectifier can be regulated by changing the firing angle of the thyristor. The capacitor located in the output filter is used to stabilize the output voltage, while the inductor is applied to improve the grid current quality [4]. Moreover, the output filter helps to eliminate the high-order harmonics.

For the transistor-based rectifier, the three-phase AC voltage is converted to a DC voltage by using the diode rectifier with a parallel smoothing capacitor. The transistors create an AC voltage of 75 kHz, as shown in example simulations later, that is connected to the primary-side of an isolation transformer. The secondary-side voltage level of the transformer can be adjusted by the transformer turns ratio and is rectified to an output voltage using fast diodes. An output filter is installed in order to reduce voltage ripple. The output voltage can be controlled by pulse width modulation of the transistor on the primary side.



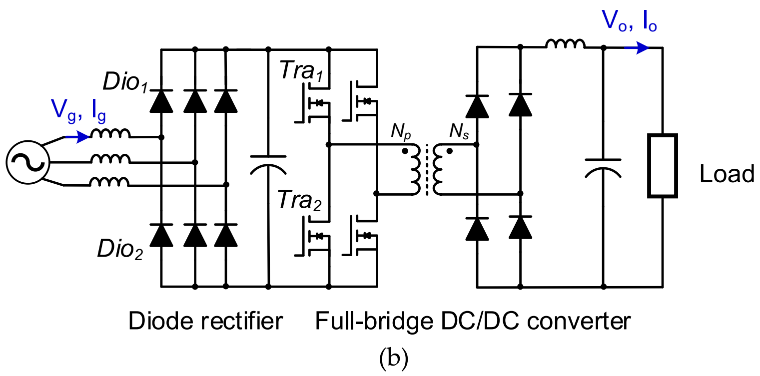


Figure 2 Topology of rectifier used in NPP. (a) Thyristor-based rectifier; (b) Transistor-based rectifier.

Table 1 Comparison between thyristor-based and transistor-based rectifiers [2], [3].

Rectifier topology	Thyristor-based	Transistor-based
Input voltage	3 * 400 Vac ±10%	3 * 400 Vac ±10%
Output voltage	110 V	110 V
Output current	60 A	60 A
Voltage ripple	5%	1%
Power factor	0.78	0.92
Efficiency	0.93	0.91
Type of cooling	Air natural cooling	Forced-air cooling
Controllability	No software or programmable device	Pulse width modulation

The specification comparison between the thyristor-based and transistor-based rectifiers is summarized in Table 1. Both the thyristor-based and transistor-based rectifiers obtain a similar range of efficiency, while the transistor-based rectifier behaves with an improved power factor and a lower output voltage ripple.

3 Ageing of power electronics, overview

This section provides the general background of ageing of power electronic components. The understandings and experiences are mainly drawn from other applications, such as renewable energy systems and industrial motor drives. Nevertheless, the component-level failure mechanisms could be relevant to broader applications, including the power electronic converters used for NPPs. For specific applications, the differences come from reliability requirements and operational and environmental conditions. It should be noted that this section focuses on the mechanisms of single failures. The interactions among failures are not included.

3.1 EXAMPLES OF FAILURE EXPERIENCES IN POWER ELECTRONIC CONVERTERS

In reliability engineering, failure is typically classified into sudden failure and degraded failure [5]. Degradation over time may cause a sudden failure, if no corrective action is taken. Sudden failure is due to design defect, manufacturing issue, single-event effect, overstress, or misuse. Degraded failure is due to long-term degradation. For a power electronic system, the failure could come from both hardware and software due to factors both intrinsic (e.g. wear out of component) and extrinsic (e.g. operational mistake). The following discussions are limited to hardware failure. Software reliability [6] and human reliability analysis [7] are not included. Nevertheless, they are important for a complete system-level reliability design and analysis. Theoretically, there are multiple failure mechanisms for a single power electronic component. At the application level, it is usually not feasible to consider all the reported failure mechanisms. A more effective way is to address a few dominant failure mechanisms relevant in field operation. The challenge is that the dominant failure mechanisms may vary with the design criteria, environmental and operational conditions in different applications.

In [5], the field experiences of photovoltaic (PV) and wind power applications have been discussed based on the following two examples. They represent two large databases for converter-specific failure analysis, which are rarely publicly available in other power electronic applications.

In the PV example originally from [8], it reveals that the power electronic part (i.e., inverter) accounts for 43% to 70% of PV plant service requests. The statistics shown in Figure 3 are drawn based on three data reports. Report 1 is based on more than 3,500 service tickets (i.e., abnormal states of PV systems) requested between 2010 and 2012, in a total of 2,800 inverter-years. Report 2 is on an older set of PV systems monitored between 2008-2010, in a total of 1,650 inverter-years. Report 3 is based on about 400 field failure events for a set of central inverters. Control software failure stands out in all three reports. This specific failure area may be the consequence of hardware malfunction, besides the software or firmware issues. It is defined as an inverter shuts down without a fault code and without being forced to disconnect due to a grid outage but resumes normal operation upon a manual restart.

In the wind power example originally from [9], the wind power converter failure analysis is given, especially for phase modules, including IGBT modules, gate driver boards, DC-link capacitors, and busbars. Phase modules are usually used in high power converter as modular building blocks to form the power conversion stage, for example, three identical modules to configure a three-phase inverter. The database used for the analysis includes

2,734 wind turbines commissioned between 1997 and 2015, operating in 23 countries across four continents from 11 suppliers. The statistics reveal that phase modules (normally including the IGBT module, gate driver boards, DC-link capacitors, and busbars) are responsible for the largest fraction of the power converter failure of, i.e., 22%, followed by the cooling system, control board, and main circuit breaker, except for the unknown failures. On average, 0.16 phase-module failure per year per turbine is observed for the turbines in the database.

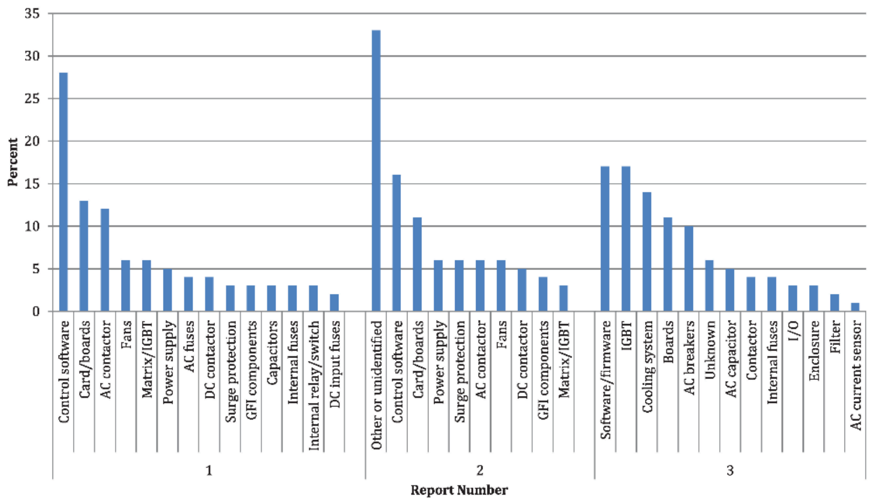


Figure 3 PV Inverter failure in percentage component breakdown from three reports, primarily for central inverters, IGBT-Insulated Gate Bipolar Transistors, GFIs – Ground Fault Interrupters [8].

3.2 CRITICAL STRESSORS AND FAILURE MECHANISMS OF POWER ELECTRONIC COMPONENTS

Focus Point Matrix (FPM), as suggested in [10], is a useful way to analyze the critical stressors that will kill the components. Based on the accumulated industrial experiences and future research needs, Table 2 shows the critical stressors for different components in power electronic systems [11]. It can be noted that steady-state temperature, temperature swings, humidity, voltage, and vibrations have a different level of impact on semiconductor devices, capacitors, inductors, and low-power control boards. It provides information on determining the critical failure mechanisms. The interactions among different stressors are also of interest to be explored.

Out of various kinds of power electronic components, power semiconductor devices/modules and capacitors are widely studied on the reliability aspects. [5], [11] and [12] have provided detailed discussions on different wear-out failure mechanisms and single-event related failure mechanisms of IGBT modules, SiC/GaN devices, and capacitors.

Table 2 Focus Points Matrix (FPM) in reliability of power electronic components [11].

Load			Focus points									
Climate + Design => Stressor			Active power components			Passive power components		Control circuitry, IC, PCB, connectors…				
Ambient	Product design	Stressors	Die	LASJ	Wire-bond	Cap.	Ind.	Solder Joint	MLCC	IC	PCB	Connectors
Relative humidity -$RH(t)$ Temperature -$T(t)$	-thermal system -operation point -ON/OFF -power $P(t)$	Temperature swing ΔT	**X**	**X**	**X**			**X**				
		Average Temperature T	X	X	X	**X**		X	X	x	x	x
		dT/dt	x	x	x	x						
		Water								**X**	**X**	x
		Relative Humidity	x	x	x	X	x	x	x	**X**	**X**	x
Pollution	Tightness	Pollution						x			x	
Mains	Circuit	Voltage	x	x	x	**X**	X		x	x	x	x
Cosmic	Circuit	Voltage	x									
Mounting	Mechanical	Chock /Vibration	x			x	x	x	x			x

LASJ - Large Area Solder Joint, MLCC - Multi-Layer Ceramic Capacitor, IC- Integrated Circuit, PCB – Printed Circuit Board, Cap. - Capacitor, Die – chip of power semiconductor.

Ind. - Inductor, Level of importance (from high to low): **X**-**X**-X-x.

3.3 DEGRADATION AND LIFETIME OF POWER ELECTRONIC COMPONENTS

1) Component degradation curve and End-of-Life (EOL) criteria (wear-out failure)

The degradation of power electronic components occurs typically at the material or interconnection level, which needs advanced physics analysis tools to identify the degradation location and structure change. Nevertheless, since the change of materials and interconnections affect the electro-thermal aspect parameters, they can be used as health precursors to estimate the degradation level indirectly. For example, on-state saturation voltage and thermal resistance between junction-to-case are widely used health precursors for IGBT modules. They are applied for both accelerated degradation testing and condition monitoring. Capacitance, Equivalent Series Resistance (ESR), dissipation factor, and insulation resistance are usually used for capacitors [12]. Figure 4 shows a generic degradation curve of a precursor corresponding to a specific failure mechanism. y is the value of the health precursor of interest. Δy is the parameter shift of the health precursor. The y-axis shows the absolute value of the percentage of change of y to its initial value y_0. Three possible distinctive stages, I, II, and III of the degradation curve, are shown. They correspond to the time intervals in which the health precursor keeps constant, increases, or decreases linearly, and increases or decreases with an accelerated pace.

It should be noted that Figure 4 is for illustration purposes only. Not all three stages necessarily appear for a specific precursor. A typical degradation curve is a combination of one or more of the three stages. The slope and percentage of each period vary for different failure precursors and stress conditions.

The time-to-failure of an individual component due to a specific wear-out failure mechanism is determined by a defined End of Life (EOL) criteria. EOL criteria are chosen by considering the component level destruct limit, system-level failure due to the parameter shift, and a certain margin, as shown in Figure 4. In practice, it is in terms of the percentage of change of y to its initial value y_0. It is reported in [13] that a 5% increase of on-state saturation voltage or a 20% increase of junction-to-case thermal resistance is used as EOL in most of the analyzed 70 publications on power cycling. 13% of publications use a 20% increase of the on-state saturation voltage as EOL. For capacitors, 20% capacitance drop, and 2-3 times increase of ESR, or dissipation factor are usually used for electrolytic capacitors [12]. The EOL in terms of capacitance drop for film capacitors is usually within the range of 2-10%.

The variety in EOL in terms of the percentage of change depends mainly on when the degradation accelerates and enters Stage III. It usually does not exactly correspond to the time when the component destruct limit or system-level failure occurs. Therefore, the change rate of y plays an essential role in defining the EOL, not necessarily the absolute value of y. It implies that component-level and system-level failure would occur soon if no action were taken at the EOL. EOL can also be decided according to the system-level requirements on the component parameter constraints.

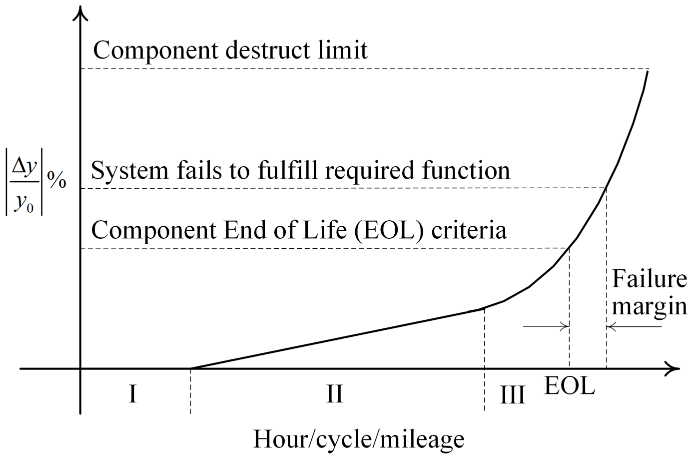


Figure 4 Three possible stages of component ageing curve. *Δy* is the parameter shift of the health precursor *y* of interest, y_0 is the initial value of the parameter *x* before testing or in use [1].

2) (Percentile) lifetime definition

Lifetime is a frequently used reliability metrics. It is for a population of the items defined at a specific reliability (or unreliability) level. For an individual item, time-to-failure is used corresponding to when the EOL is reached. Figure 5 shows a Weibull plot [1] of the unreliability curve. The curve is usually based on the time-to-failure data of a limited number of samples for the item of interest. The confidence intervals illustrate the uncertainties in Figure 5. The solid line and dashed line represent 50% and 95% confidence level, respectively. B_X lifetime is used to define the (percentile) lifetime corresponding to the time when there is *X*% of accumulated failure. It can be noted that the obtained lifetime varies with different X% and confidence level. B0.1_95% implies 95% probability that 0.1% of the population of items fail until the time. In other words, statistically, there is 5% risk that more than 0.1% items fail until the time. B10_50% implies 50% probably that 10% of the items fail until the obtained lifetime value. Moreover, the plots shown in Figure 5 are for specific environmental and operational conditions. Therefore, a comprehensive lifetime definition should include the following four aspects:

a) The environmental and operational conditions
b) The EOL used for determining the time-to-failure
c) The corresponding percentage of accumulated failure (X%)
d) The confidence levels

Nevertheless, such comprehensive information is rarely provided in the literature when the lifetime is stated, making it unknown to the implication for failure and associated risk. If any aspect of the information is missed, a lifetime comparison would be in question. Moreover, the B_X lifetime with a certain confidence level is a single point in the unreliability curve. The same B_X lifetime for two different items does not necessarily imply the same reliability in the entire service life, as the curve slope could be different.

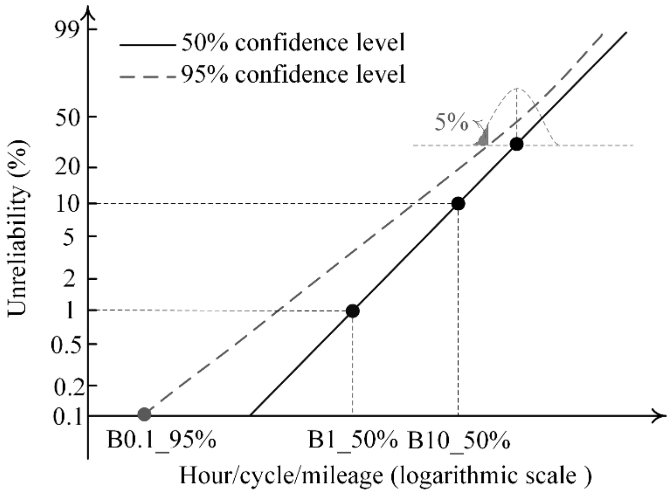


Figure 5 Illustration of percentile lifetime definition under different confidence levels for a specific wear out failure mechanism based on time-to-failure data in a Weibull plot [1].

3.4 MONITORING OF RECTIFIER SYSTEMS

3.4.1 Background of condition and health monitoring

Condition and Health Monitoring (CHM) is a reliability engineering tool to unlock the emerging opportunities in operation optimization, predictive maintenance, and digital service for power electronic converters. The term CHM may have slightly different definitions and scopes in the literature. It refers to the acquisition and processing of information used for estimating the operational parameters and degradation states of an item in this report. It can be conducted automatically during operation or at planned intervals. CHM is a reliability engineering tool used in the operation phase, in addition to other tools used in the design and manufacturing phases [14]. Design and manufacturing are foundational to build in product reliability and availability. CHM is ancillary depending on if it can create net value to the application of interest.

In power electronics applications, CHM could bring the following possible values: 1) provide necessary component in-situ parameters and stress conditions used for derating, adaptive control, or protection; 2) provide the degradation states used for decision-making in maintenance or lifetime extension; 3) minimize excessive design margins, and 4) collect data from power electronic converters for further exploitation. The first three aspects aim for life-cycle-cost reduction and more competitive service. The last aspect aligns with the trend for exploring new opportunities in digitalization and data-driven-based approaches in power electronics. Nevertheless, the implementation of CHM does increase the system-level complexity in terms of added software algorithm, hardware circuitry, or both, implying possible new risk and reduced reliability before any maintenance action is taken. Therefore, the values created by CHM need to be weighed against the cost and potential risk associated with the technical solutions.

3.4.2 Introduction to CHM indicators for power electronic converters

CHM obtains the stress conditions or estimates the health states of the item of interest. The latter is usually based on “symptoms,” which can be observed through direct or indirect stresses or parameters, i.e., indicators. This section introduces the types of CHM indicators and the practical considerations in choosing them for power electronic applications.

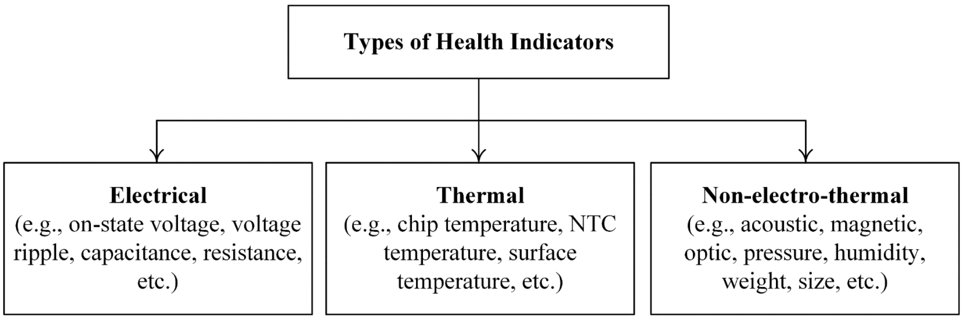


Figure 6 Types of health indicators reported for CHM of power electronic converters.

1) Types of health indicators

Health indicators directly or indirectly indicate the health conditions of power electronic components correlated to specific degradation and failure mechanisms. The dominant degradation and failure mechanisms in a specific application largely depend on its design, manufacturing, and field operation mission profile. As shown in Figure 6, they can be classified into electrical, thermal, and other types of parameters. Theoretically, the values of many of these indicators would change if degradation or fault occurs. Nevertheless, they are usually affected by other factors, e.g., temperature, loading conditions, and measurement errors. In practice, one or multiple health indicators may be used. Converter-level and component-level health indicators are briefly introduced below.

Converter-level health indicators can reveal the overall converter conditions and provide information for decision-making for converter-level operation optimization and maintenance, which are not necessarily used for locating individual components of concern. For example, AC current signature, AC voltage signature, and converter efficiency could indirectly indicate the health status or abnormal operation of power converters.

Component-level health indicators are related to respective critical components or interconnections. They can monitor the condition and health status at the component level when the converter-level health indicators alone cannot provide a satisfactory solution. Examples are power module Negative Temperature Coefficient (NTC) temperature, power semiconductor on-state saturation voltage, capacitor surface temperature, capacitor capacitance and equivalent series resistance (ESR), and interconnection surface temperature.

2) **Practical considerations and challenges in health indicator measurement or estimation**

   a) *Simplicity* – it should be noted that added condition monitoring solutions (i.e., in the form of software, hardware, or both) reduce the system's reliability to be monitored (before maintenance) due to increased complexity and bring potential new risks. Therefore, simplicity in implementation is key (including any associated calibration procedure) to minimize the impact.
   b) *Robustness* – sensitivity to degradation and failure, and sensitivity to other noise factors, such as operation and environmental conditions. To improve the robustness, calibrations and advanced data analyses may be needed.
   c) *Accuracy* – two types of errors are of concern at the application level. Type I – normal states are incorrectly indicated as degraded or failure states; Type II – degraded or failure states are not detected or predicted. Reducing these two types of errors demands a certain accuracy level in health indicator measurement or estimation, which is usually constrained by the sensor accuracy, sampling frequency, and other noise factors.

3.4.3 Outlook in CHM for power electronic converters

The demand for CHM in power electronics applications is increasing. The market for digital service is emerging with the rapid development and massive implementation of power electronics in various applications. Existing research efforts have been devoted mainly to power modules and capacitors and up to the health indicator measurement or estimation [15]. There is still a lack of reported case studies on other components and further steps beyond the health indicator measurement or estimation. To a large extent, mature solutions are not available yet for massive industry applications, to the authors' best knowledge. Nevertheless, existing research provides a foundation for application-level technology improvement, integration, and demonstration. Below is an outlook for future needs and research opportunities.

1) **Define application-level specifications**

   Application-level specifications could impose quite different requirements, trade-offs, and constraints of a specific CHM solution. Here are a few question examples to help define the specifications. Is there a value proposition to have the CHM? Is it for health state prediction, stress condition estimation, or another purpose? Is it for a new design or retrofit of an existing system? Is it for continuous or intermittent monitoring? Is it necessary to locate individual components or not? Are there special operation modes that can be used? What are the constraints in the accessibility to the converters? What are the limitations in sensor accuracy and sampling frequency? What are the accuracy requirements for CHM?

2) **Bridge the gaps between lab verification and field testing**

   Common limitations observed in the literature are relatively well-controlled environments and limited testing samples and scenarios. Nevertheless, the noise level may differ significantly from field operation due to different environments and operation profiles. Furthermore, considering the initial tolerances, a calibration method feasible for a low number of systems may not be economical-wise for a high population. Therefore, trial field testing helps identify challenges that lab testing may not encounter. There is an opportunity to relax the requirements in health indicator accuracy and calibration effort by advanced data processing and compensation.

3) Demand for minimizing the new risk of CHM to the system to be monitored

New risk could come from two aspects. Firstly, the malfunction of the introduced hardware or software for CHM. Secondly, the decision-making based on incorrect CHM results may lead to unnecessary actions. Therefore, non-invasive, and straightforward solutions are desirable. Furthermore, research in non-electrical health indicators could open new possibilities since they are less coupled with the primary function of power converters. It is also crucial to quantify the new risk weighed with the created value by CHM.

4) Utilize special operation modes

For applications in which continuous monitoring is not required, methods based on information from special operation modes might enable new opportunities in simplified solutions.

5) Leverage both the latest advancements in data-driven approach and physical aspects understanding of power electronic converters

In [16], Artificial Intelligence (AI) application for CHM of power electronic converters is discussed. The bottleneck is usually on obtaining good data for computational-efficient training in engineering applications. Therefore, methods that can leverage both AI and existing deterministic models are promising to reduce data and computation power requirements.

4 Ageing of power electronics in NPP

4.1 INTERVIEWS WITH NPP OWNERS

Interviews were performed with NPP owners to compile a detailed picture of the status and experiences from currently installed equipment in respective plant. Aim of interviews were to get collect information regarding

- the rectifier system configuration in the plant context and in detail topology of the system (key components)
- system status and reasons for any performed exchanges
- environmental and operational factors that might impact ageing
- data and experience of ageing and failing equipment
- maintenance and monitoring routines

The results from interviews are presented in Table 3. As the information from respective plant was generally similar it is here presented per area of questions as a Summarized result.

Table 3 Summarized result from interviews with NPP owners (FKA, RAB, OKG, Fortum, TVO)

Area	Summarized result
Components	Thyristor or switched mode rectifier or a mix of both.
Environmental conditions, temperature, and humidity	Dry with normally small temperature variations.
Environmental conditions, electrical	Controlled electrical conditions with no, or small variations.
Operational conditions	Normal load is low, maximum 25-50%. Systems are always implemented with redundancy, i.e. rectifier in each part is dimensioned to handle the entire load.
Transients, experienced or assumed risks	Few real experiences or transients (internal or external). NPPs have taken experiences from incident in Forsmark into account implementing surge protection.
Error statistics	Few errors leading to interrupted function. Most errors are seen in control electronics, relays, capacitors.
Maintenance	Exchanges according to supplier recommendations. Visual inspections. If condition-based maintenance is applied it is based mainly on inspection and in few cases measurement.

System status and planned exchanges	Some have performed exchanges, other plan for exchanges in near time.
Reasons for exchange/planned exchange	Main reason for exchanging equipment is obsolescence of spare parts. Simplified maintenance with module-based design is one advantage often mentioned with new equipment.
Applied requirements for the Class 1E DC systems	TBE 120, YVL B.1 and E.7 EN, IEC and KTA

A general experience from the interviews is that the system configuration in the plant context is similar although the topology and key components might vary to some extent. The NPPs have chosen slightly different approaches regarding the choice of component design which can be divided into thyristor-based or switched mode or transistor-based rectifiers. Environmental and operational conditions are in general favorable from an ageing point of view, with controlled temperature and low humidity and small variations in electrical conditions. The system normal load is low and there are few real events where known transients have hit the components in the system. Maintenance is performed mainly time based including visual inspections and exchange of components based on supplier recommendations.

4.2 RELEVANT AGEING MECHANISMS

According to interview results in Table 3, it can be generally concluded that the variation from "mains" is the key ageing mechanism as shown in Table 4.

Table 4 Key ageing mechanism of power electronics in rectifier systems in NPPs highlighted in the Focus Points Matrix (FPM) for reliability of power electronic components.

Load			Focus points									
Climate + Design => Stressor			Active power components			Passive power components		Control circuitry, IC, PCB, connectors…				
Ambient	Product design	Stressors	Die	LASJ	Wire-bond	Cap.	Ind.	Solder Joint	MLCC	IC	PCB	Connectors
Relative humidity -$RH(t)$ Temperature -$T(t)$	-thermal system -operation point -ON/OFF -power $P(t)$	Temperature swing ΔT	**X**	**X**	**X**			**X**				
		Average Temperature T	X	X	X	**X**		X	X	x	x	x
		dT/dt	x	x	x	x						
		Water								**X**	**X**	x
		Relative Humidity	x	x	x	X	x	x	x	**X**	**X**	x
Pollution	Tightness	Pollution						x			x	
Mains	Circuit	Voltage	x	x	x	**X**	X		x	x	x	x
Cosmic	Circuit	Voltage	x									
Mounting	Mechanical	Chock /Vibration	x			x	x	x	x			x

Energiforsk

5 Analysis

5.1 GRID VARIATION IMPACTS

5.1.1 Voltage amplitude variation

As aforementioned, typical rectifier systems can be divided into thyristor-based rectifier and transistor-based rectifier. The operation performance under the normal grid condition and the variation of the voltage amplitude will be investigated.

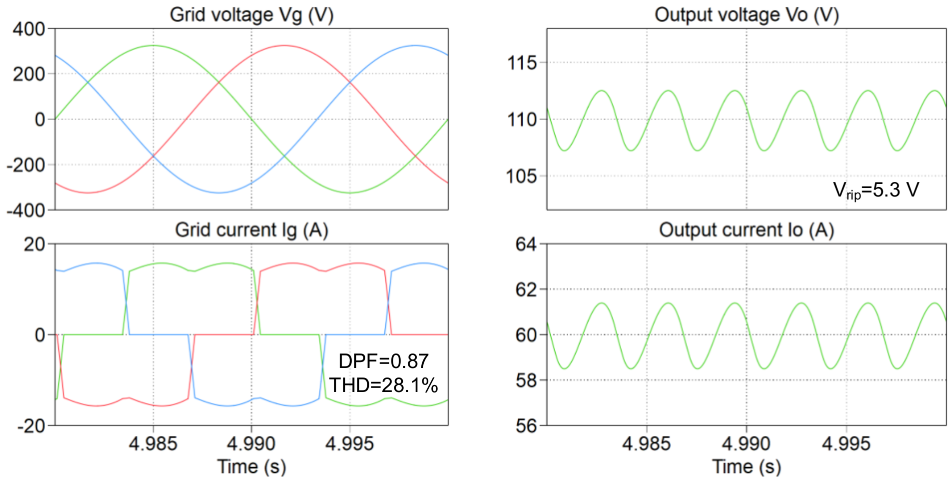
For the thyristor-based rectifier, since the firing angle of the thyristor determines the phase angle of conducting current in relation to the grid voltage, the power factor of the thyristor rectifier is dependent on the firing angle. In order to follow the power factor of 0.78 [2], the firing angle needs to be less than 38.7°. Meanwhile, the output voltage of the thyristor rectifier is closely related to the firing angle and rectifier input voltage. The transformer ratio of 4:1 is calculated according to the values of the grid voltage and output voltage. Normally, a dc-link capacitor is applied to reduce the voltage ripple from the thyristor rectifier, which makes the grid current discontinuous and worsens the total harmonic distortion (THD). To improve the THD level, both the DC choke and the AC line reactor can be employed [21], [22]. A typical design of DC choke with 5.2% impedance is applied, and the leakage inductance of the line transformer is considered as 5.2% impedance. The key parameters of the thyristor-based rectifier used for the analysis are summarized inTable 5.

Table 5 Specification and key parameters for thyristor-based rectifier (values are estimated from product specification).

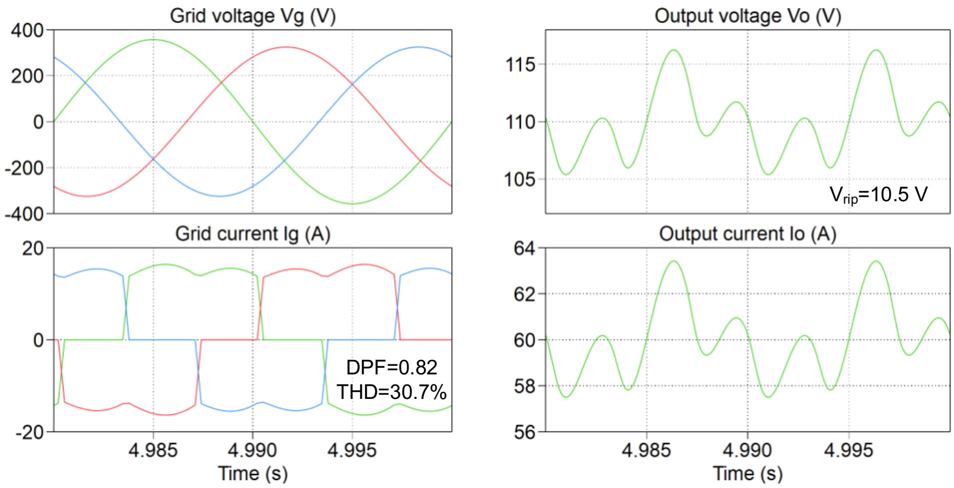
Rectifier topology	Thyristor-based
Input voltage	3 * 400 Vac ±10%
Output voltage	110 V
Output current	60 A
Ratio of line transformer	4:1
Transformer leakage inductor	1 mH
DC choke	4 mH
DC-link capacitor	600 μF

Under the normal grid condition, the simulation results of the rectifier input and output are shown in Figure 7(a). V_g and I_g denote the grid voltage and current, while V_o and I_o denote the output DC voltage and current. For the grid side, it can be seen that the DC choke almost keeps the flat grid current, while the AC line reactor introduces the thyristors commutation. Moreover, the grid current has a displacement power factor (DPF) of 0.87 and THD of 28.1% [23]. For the output side, the ripple voltage fluctuates six times within a line frequency, and the ripple voltage V_{rip} is 5.3 V, which is less than 5% of the output voltage.

In the case that the voltage in one single-phase becomes 1.1 times of the normal value, the corresponding simulation results are shown in Figure 7(b). The asymmetrical grid voltage leads to the unbalanced current, where the worst DPF and THD become 0.82, and 30.7%, respectively. For the output behaviour, the output voltage fluctuates twice within a line frequency, and the voltage ripple becomes 10.5 V, which is much higher compared to the normal condition.



(a)



(b)

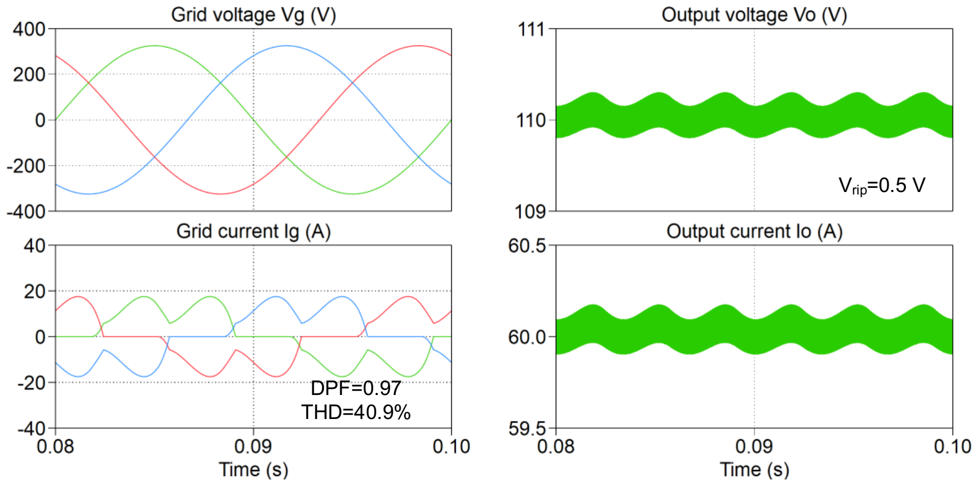
Figure 7 Simulation results of the thyristor-based rectifier. (a) Input and output behaviors under the normal grid; (b) Input and output behaviors under the asymmetrical grid.

Table 6 Specification and key parameters for transistor-based rectifier (values are estimated from product specification).

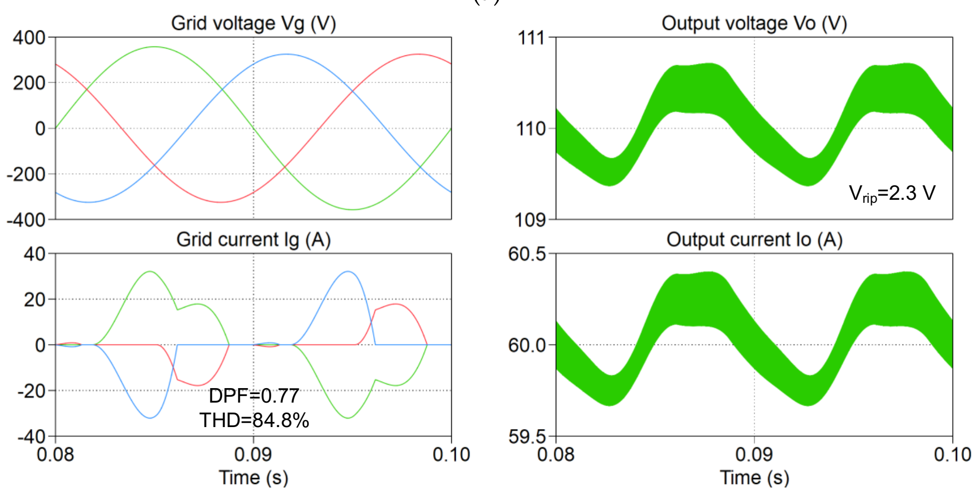
Rectifier topology	Transistor-based
Input voltage	3 * 400 Vac ±10%
Output voltage	110 V
Output current	60 A
Line reactor	2.5 mH
DC-link capacitor	600 μF
Transformer ratio	4:1
Switching frequency	75 kHz
Output filter inductor	60 μH
Output filter capacitor	5 μF

For the transistor-based rectifier, it consists of the front-end diode rectifier and the rear-end full-bridge DC/DC converter. The diode rectifier is equipped with an AC line reactor of 3.3% impedance. Although the line reactor slightly reduces the dc-link voltage, it is calculated that the output voltage range from the diode rectifier is between the line-to-line voltage and 0.866 of this value. Meanwhile, the full-bridge DC/DC converter behaves as the Buck converter, which steps down the input voltage. As a result, the transformer ratio is set at 4:1, which guarantees the input voltage of the DC/DC converter is higher than the output voltage. In addition, the inductor and capacitor values of the output filter can be determined by the specification of the current and voltage ripples. The key parameters of the transistor-based rectifier are listed in Table 6.

In the case of the normal grid, the input and output behaviour of the transistor-based rectifier is shown in Figure 8(a). It can be seen that the grid current is almost in the phase of the grid voltage, which leads to the DPF of 0.97. Meanwhile, the output ripple voltage is within 0.5 V due to the fast regulation with the 75 kHz switching frequency. Compared with the thyristor-based rectifier, the transistor-based rectifier has a better DPF and lower ripple voltage.



(a)



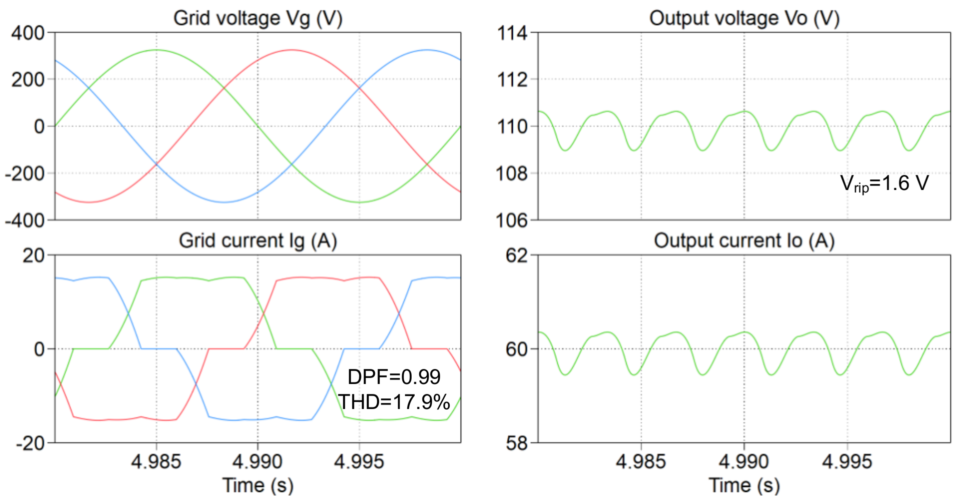
(b)

Figure 8 Simulation results of the transistor-based rectifier. (a) Input and output behaviors under the normal grid; (b) Input and output behaviors under the asymmetrical grid.

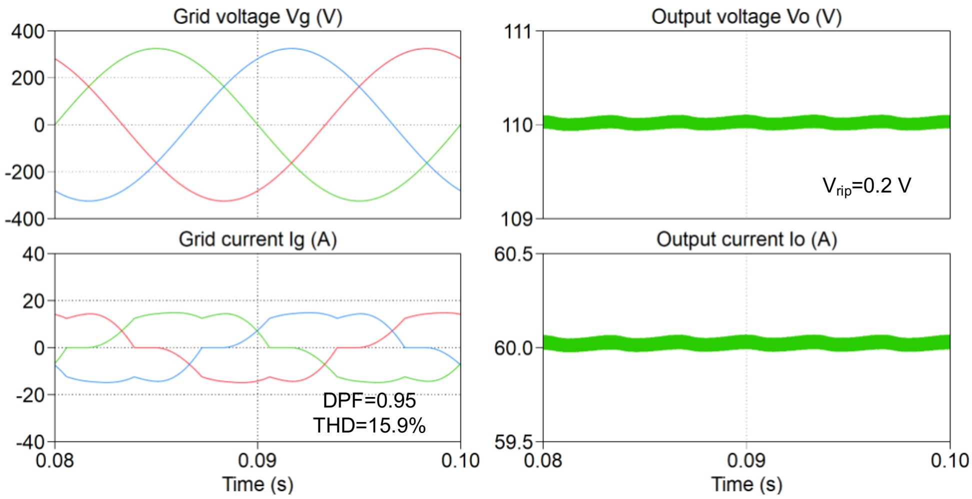
When the grid voltage becomes asymmetrical with the swell factor of 1.1 in a single phase, the simulation results are shown in Figure 8(b). The grid current becomes quite asymmetrical with the worst DPF of 0.77, and the output ripple voltage increases to 2.3 V. Regardless of the thyristor-based and transistor-based rectifiers, the asymmetrical grid voltage deteriorates the ripple voltage and the DPF.

The strength of the grid is defined by the Short Circuit Ratio (SCR), which indicates the ratio of short circuit power at the point of common coupling and the rated power of the rectifier. When the SCR is below 6-10, the grid can be considered as weak. In the case that the SCR is above 20, the grid becomes strong [24]. By considering the transformer leakage inductance of the thyristor-based rectifier and the AC line reactor of the transistor-based rectifier, the value of SCR is higher than 20 under both cases, featuring the strong grid. In the case of the weak grid, where the SCR becomes 5, the performance of the thyristor-based rectifier and the transistor-based rectifier is evaluated in Figure 9. It is evident that, from the input side of the rectifiers, the

THD is remarkably improved due to the higher grid impedance. In addition, the ripple voltage becomes significantly lower compared to the strong grid.



(a)



(b)

Figure 9 Rectifier performance under weak grid (SCR = 5), (a) Input and output behaviors of thyristor-based rectifier; (b) Input and output behaviors of transistor-based rectifier.

The service lifetime of a battery is specified in a number of discharging and charging cycles that the capacity fade and impedance rise can still maintain within the acceptable range. Battery manufacturers recommend that under normal float charge conditions, battery ripple voltage must be limited to 0.5% of the DC voltage applied to the battery [25], [26]. It is worthwhile to note that the ripple voltage is defined by the RMS (root mean square) value. If a sinusoidal voltage ripple is assumed, the RMS value is times of the peak-to-peak value, which is presented in the previous simulation results. This ensures that the instantaneous cell voltage will not fall below the open cell voltage or rise the maximum float charge voltage. In the case of a ripple voltage, the internal impedance of the battery leads to the ripple current, and thereby the power dissipation is introduced. As indicated in [25], the temperature rise of the battery reduces the service lifetime. It can be expected that the higher ripple voltage from the thyristor-based rectifier deteriorates the battery performance. Moreover, the higher voltage ripple from asymmetrical grid conditions is harmful to the reliable operation of battery systems. Furthermore, since the voltage ripple caused by the thyristor-based rectifier is mainly the low frequencies (several times of the line frequency), it experiences a higher impedance increase and capacity fade than battery cells with high AC frequencies [27].

5.1.2 Surge voltage

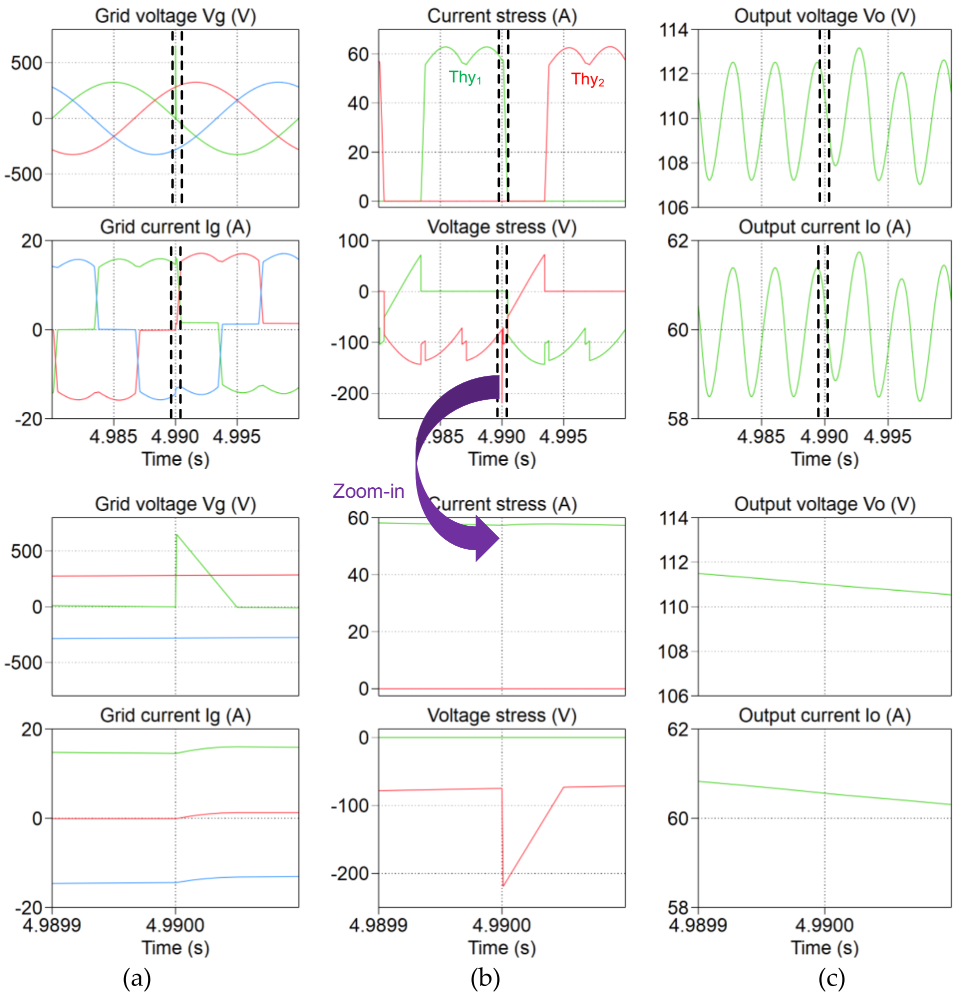


Figure 10 Surge voltage impact on current and voltage stress of the power semiconductor in the thyristor-based rectifier, (a) Input-side voltage and current; (b) Voltage and current of thyristors; (c) Output-side voltage and current.

A voltage surge is defined as the sudden rise in excessive voltage, which may damage the electrical equipment of an installation. It can be caused by internal or external reasons. Internal over-voltage can be caused by the operation of circuit breakers when switching inductive or capacitive loads, while external over-voltage is caused by atmospheric discharge such as lightning strikes.

A varistor is commonly applied to shunt the over-voltage, which is known as a metal oxide varistor (MOV). When the surge voltage does not exceed the varistor voltage, the varistor works as a capacitor. However, when the surge voltage exceeds the varistor voltage, the impedance across the varistor terminals decreases sharply. As the input voltage to the circuit depends on the varistor internal resistance and line impedance, the decrease in the impedance across the varistor terminals allows surge voltage protection.

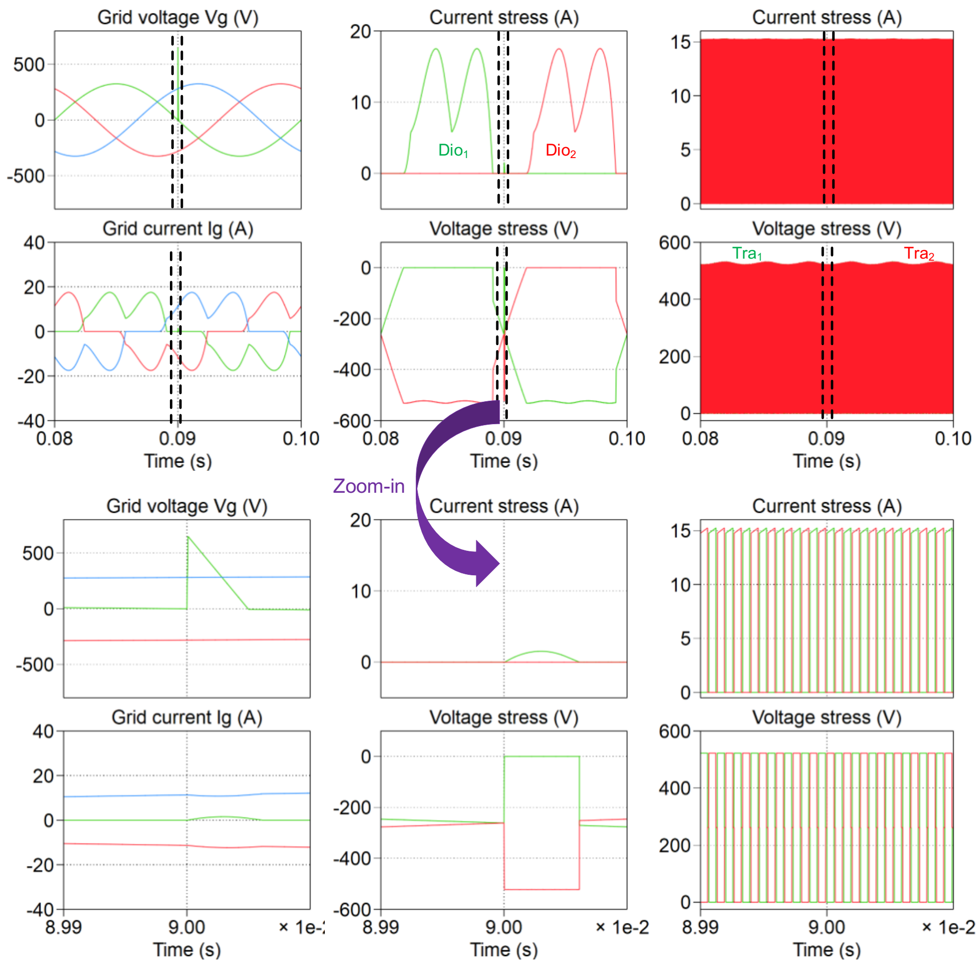


Figure 11 Surge voltage impact on current and voltage stress of the power semiconductors in the transistor-based rectifier, (a) Input-side voltage and current; (b) Voltage and current of front-end diode rectifier; (c) Voltage and current of rear-end transistors.

Semiconductor components are known for being sensitive to over-voltage. If the maximum rated voltages given in the datasheet are exceeded, the component might be destroyed. For this reason, the components have to be protected from any excessive voltage that might occur in any of the circuits. Snubber circuits (resistor and capacitor elements) have proven to be a reliable way [17]. In addition, the thyristor has a much higher over-current capability compared to the transistor. The power semiconductors are selected with a similarly rated current [18], [19]. However, it can be seen that the surge current of the thyristor is almost 20 times of the rated on-state current, while the transistor can withstand the peak current with 2 times of the rated drain current.

In order to evaluate the transient performance of the power semiconductors, a typical surge voltage [20] applied to both the thyristor-based and transistor-based rectifiers, as shown in Figure 10 and Figure 11, respectively. For the thyristor-based rectifier, it is noted that the voltage stress of the thyristor becomes much higher, while the current stress remains the same as the case without the surge voltage. In respect to the transistor-based rectifier, it can be found the current and voltage stress of the transistor remain unchanged, but the front-end diode conducts for a short period during the surge voltage.

5.2 REDUNDANCY

By using the concept from statistical analysis, the probability density function (PDF) is used to describe the failure distribution of the component. The Weibull distribution is generally preferred, as it can widely represent the typical distributions such as normal distribution, exponential distribution, and it can be expressed as,

$$f(\mathrm{t}) = \frac{\beta}{\eta} t^{\beta-1} \exp[-(\frac{t}{\eta})^{\beta}] \tag{1}$$

where β denotes the shape parameter, and η denotes the scaling parameter. In the case of $\beta=1$, the Weibull distribution is identical to the exponential distribution. In the case of $\beta=3.5$, the Weibull distribution approximates the normal distribution.

The failure function or unreliability function is the integral of the PDF until the current time, which can be calculated as,

$$F(\mathrm{t}) = 1 - \exp[-(\frac{t}{\eta})^{\beta}] \tag{2}$$

Since the integral of the PDF throughout the time frame is 1, the reliability function is defined as the integral from the current time until the infinite. Consequently, the reliability function can be expressed,

$$R(\mathrm{t}) = \exp[-(\frac{t}{\eta})^{\beta}] \tag{3}$$

To link the reliability from the component level to the system level, the reliability block diagram is a typical way to assist. When the components are series-connected, the failure of any component leads to the failure of the system. Then, the reliability function of the system is the product of the component reliability function,

$$F_{sys}(\mathrm{t}) = 1 - (1 - F_{com}(\mathrm{t}))^{n} \tag{4}$$

where F_{sys} denotes the unreliability function of the system, F_{com} denotes the unreliability function of the component, and n denotes the number of the component.

When the components are parallel connected, the failure of the whole components leads to the system failure. The unreliability function of the system is product of the component unreliability function,

$$F_{sys}(\mathrm{t}) = F_{com}(\mathrm{t})^{n} \tag{5}$$

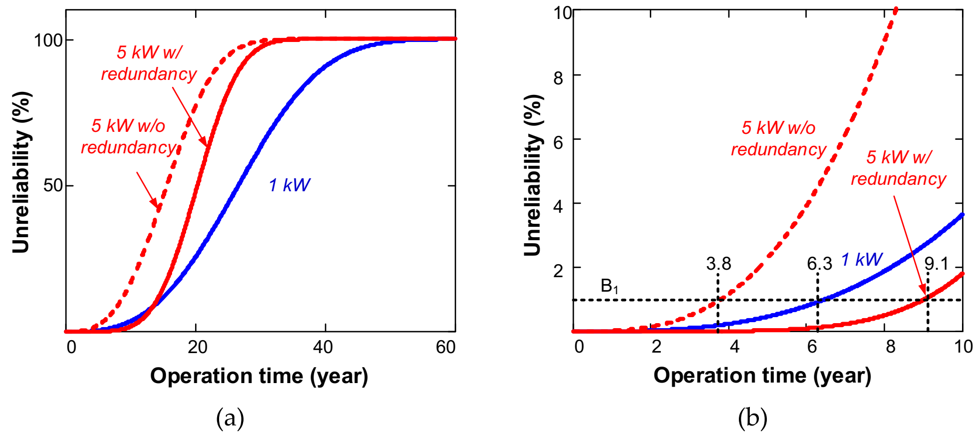


Figure 12 Unreliability curve of the component and system with and without the redundancy. (a) Overview; (b) Zoom-in of *B₁* lifetime.

In the case of m-out-of-n redundancy, the unreliability function of the system can be expressed as [28],

$$F_{sys}(t) = \sum_{i=0}^{m-1} \frac{n!}{i!(n-i)!} \cdot (1 - F_{com}(t))^i \cdot F_{com}(t)^{n-i} \tag{6}$$

Assuming a 5 kW power stage is realized by using the parallel connection of an individual 1 kW power converter. If there are five power converters, the system is connected without redundancy. If there are six power converters, the system is with N+1 redundancy. Assuming the Weibull distribution of a 1 kW power converter with a shaping parameter of 3 and a scaling parameter of 30, the unreliability function of the component and system are presented in Figure 12.

The overall unreliability curve of the whole power stage is shown in Figure 12(a), where the cases with and without redundancy are compared as well. Due to the fact that five reliability blocks are serially connected in the condition without redundancy, the lifetime of the power stage is significantly reduced compared to a 1 kW power converter. However, in the case of using redundancy, the reliability of the power stage can be enhanced compared with no redundancy. Specifically, as shown in Figure 12(b), if the B_1 lifetime is in concern, where the component will have 1% probability to fail, the lifetime of the individual power converter is 6.3 years. It can be seen that the B_1 lifetime of the power converter without redundancy is reduced to 3.8 years, while it can be enhanced to 9.1 years with N+1 redundancy.

6 Conclusions and recommendations

6.1 CONCLUSIONS

The following conclusions are based on the relevant literature study, interviews, and case studies conducted during the project. It is based on the best information the project team can obtain at the time when the report is prepared. Nevertheless, since the reported failure experiences in the power electronic converters of interest are still limited, it requires further studies, as recommended in the next sub-section, to come up with more conclusive conclusions.

1) Other applications, such as wind power plants, photovoltaic plants, and e-mobility, have shown that power electronic converters are reliability-critical sub-systems. Among various kinds of components, power semiconductor modules, capacitors, and interface connections stand out in terms of failure. A difference is that power converters in those applications usually operate at a much higher percentage of loading with respect to their specified ratings than those used in nuclear power plants. Nevertheless, the common aspect is that peaks and transients could occur in the grid which may cause the failure of power electronic components independent of loading conditions.

2) It is unlikely to have wear-out failure of the power electronic components due to the relatively light load operation of the rectifiers. One exception could be the electrolytic capacitors since environments alone (e.g., temperature) can cause degradation (i.e., defined by shelf-life).

3) The single-event effect, over-stress, misuse, or design defect can cause the sudden failure of electronic components, which can be independent of the power level. An example is grid voltage peaks and transients, which may lead to over-voltage stress of power semiconductor switches and capacitors.

4) Thyristor-based rectifiers have higher over-current capability from the power semiconductor device perspective. Transistor-based rectifiers achieve better operational performance (e.g., lower output voltage ripple, and higher power factor), which have lower ripple currents and less impact on the degradation of the batteries to be charged. Moreover, the higher voltage ripple from asymmetrical grid conditions is harmful to the reliable operation of battery systems. The simulation results under weak grid condition shows that the weaker power grid leads to lower THD of the grid current and lower output voltage ripple.

5) Routine-based maintenance of power electronic converters is the practice of existing nuclear power plants according to the interviews presented in Chapter 4. Predictive maintenance is emerging in other power electronics application areas, such as wind energy, photovoltaic, and e-mobility. It is therefore of interest to investigate further whether it creates new values in nuclear power plant application by minimizing the risk associated with sudden failure as defined in section 3.1.

6.2 RECOMMENDATIONS

1) Collect representative voltage and current data of mains to be able to do further failure cause analysis. The peaks and transients from the mains are likely a critical factor causing rectifier failure. Measurements should be designed based on recommendations according to e.g. IEEE standard (IEC 61000-4-5). Data could be compared to experiences from other industry applications to evaluate how the transients and peaks hitting the components in a NPP can be impacting ageing and reliability.

2) Investigate further the performance of the front-end protection of the rectifiers in the presence of peaks and transients from the mains. The integrity of the protection devices (e.g., varistors) is critical to prevent over-stress failure of power semiconductor devices and capacitors used in the rectifiers.

3) Investigate the shelf-life of electrolytic capacitors. Wear-out failure due to electro-thermal stresses is unlikely under light load conditions if the rectifiers in use are properly designed. Nevertheless, electrolytic capacitor degradation (e.g. the vaporization or leakage of electrolyte) could happen even under environmental conditions without electrical loads. Therefore, the capacitors need to be sized with enough shelf-life.

4) Study the feasibility and the level of demands for alternative maintenance strategies (e.g. condition-based) than routine-based ones. Predictive maintenance based on condition monitoring of power electronic converters is emerging in other fields, such as wind, photovoltaic, and e-mobility. Whether or not this will create new values to nuclear power plant application requires further analysis as outlined in section 3.4.3.

5) Study the feasibility of a new redundancy strategy by increasing the number of rectifiers with lower power ratings. Since the rectifiers usually operate at light loads, it may increase the overall reliability by splitting each of the existing rectifiers into two with half of the power rating. The total power rating of the rectifiers keeps the same and the system has a higher level of redundancy. The idea is to let the power converter operate close to the rated power for higher efficiency.

7 References

[1] International Atomic Energy Agency, “Design of Electrical Power Systems for Nuclear Power Plants,” IAEA Safety Standards Series No. SSG-34, IAEA, 2016.

[2] AEG PROFITEC S N1 Product Sheet. (https://www.aegps.com/en/products/dc-systems-industrial/profitec-s-n1/)

[3] AEG AC7000 N1 Product Sheet. (https://www.aegps.com/en/products/dc-modules/ac-7000-n1/)

[4] J. W. Kolar and T. Friedli, "The Essence of Three-Phase PFC Rectifier Systems—Part I," *IEEE Transactions on Power Electronics*, vol. 28, no. 1, pp. 176-198, Jan. 2013.

[5] H. Wang and F. Blaabjerg, “Power electronics reliability: state of the art and outlook,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 6476 – 6493, Dec. 2021.

[6] M. R. Lyu (editor), *Handbook of software reliability engineering*, McGraw-Hill, 1996.

[7] L. Podofillini, *Human reliability analysis*, book chapter from Handbook of safety principles, Wiley, 2017.

[8] P. Hacke, S. Lokanath, P. Williams, A. Vasan, P. Sochor, G. TamizhMani, H. Shinohara, and S. Kurtz, "A status review of photovoltaic power conversion equipment reliability safety and quality assurance protocols", *Renewable and Sustainable Energy Reviews*, vol. 82, no. 1, pp. 1097-1112, Feb. 2018.

[9] K. Fischer, K. Pelka, A. Bartschat, B. Tegtmeier, D. Coronado, C. Broer, and J. Wenske, “Reliability of power converters in wind turbines: Exploratory analysis of failure and operating data from a worldwide turbine fleet,” *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6332 – 6344, Jul. 2019.

[10] ZVEL, *Handbook for robustness validation of automotive electrical/electronic modules*, revised version, Jun. 2013.

[11] H. Wang, M. Liserre, F. Blaabjerg, P. de P. Rimmen, J. B. Jacobsen, T. Kvisgaard, and J. Landkildehus, "Transitioning to physics-of-failure as a reliability driver in power electronics," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 1, pp. 97-114, Mar. 2014.

[12] H. Wang and F. Blaabjerg, “Reliability of capacitors for DC-link applications in power electronic converters – an overview,” *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3569-3578, Sep./Oct. 2014.

[13] C. Durand, M. Klingler, D. Coutellier, and H. Naceur, "Power cycling reliability of power module: A survey", *IEEE Trans. Device Mater. Rel.*, vol. 16, no. 1, pp. 80-97, Jan. 2016.

[14] H. Wang and F. Blaabjerg, “Power electronics reliability: state of the art and outlook,” IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 6, pp. 6476 – 6493, Dec. 2021.

[15] S. Zhao and H. Wang, “Enabling data-driven condition monitoring of power electronic systems with artificial intelligence: concepts, tools, and developments,” IEEE Power Electronics Magazine, vol. 8, no. 1, pp. 18 – 27, Mar. 2021.

[16] H. Wang, Y. Peng, and X. Wei, “Perspective on condition and health monitoring of power electronic converters,” in Proc. CIPS 2022.

[17] Semikron Application Notes, “application manual power semiconductors”. (https://www.semikron.com/service-support/application-manual.html)

[18] TT104N dataheet. (https://www.infineon.com/dgdl/Infineon-TT104N-DataSheet-v03_03-EN.pdf?fileId=db3a304412b407950112b42f760f4ba5)
[19] IMZA120R020M1H dataheet. (https://www.infineon.com/dgdl/Infineon-IMZ120R030M1H-DataSheet-v02_02-EN.pdf?fileId=5546d46269e1c019016a92fdcc776696)
[20] Wikipedia IEC61000-4-5 (https://en.wikipedia.org/wiki/IEC_61000-4-5).
[21] Schneider Electric Application Notes, "Variable Speed Drives: The Advantages of DC Chokes versus AC Line Reactors Data Bulletin". (https://www.se.com/us/en/download/document/8800DB1705/)
[22] K. Lee, D. Carnovale, D. Young, D. Ouellette, and J. Zhou, "System Harmonic Interaction Between DC and AC Adjustable Speed Drives and Cost Effective Mitigation," *IEEE Trans. on Industry Applications*, vol. 52, no. 5, pp. 3939-3948, Sept.-Oct. 2016.
[23] Definition of power factor and total harmonic distortion. (Online: https://en.wikipedia.org/wiki/Power_factor)
[24] A. Etxegarai, P. Eguia, E. Torres, A. Iturregi, and V. Valverde, "Review of grid connection requirements for generation assets in weak power grids", *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1501-1514, 2015.
[25] Technical Note from Emerson, "Effects of AC Ripple Current on VRLA Battery Life". (https://datacsi.com/wp-content/uploads/white-papers/Effects-of-AC-Ripple-Current-on-VRLA-Battery-Life-Technical-Note-TN-00008.pdf)
[26] K. Uddin, A. D. Moore, A. Barai, J. Marco, "The effects of high frequency current ripple on electric vehicle battery performance", *Applied Energy*, vol. 178, pp. 142-154, 2016.
[27] M. J. Brand, M. H. Hofmann, S. S. Schuster, P. Keil and A. Jossen, "The Influence of Current Ripples on the Lifetime of Lithium-Ion Batteries," *IEEE Trans. on Vehicular Technology*, vol. 67, no. 11, pp. 10438-10445, Nov. 2018.
[28] P. D. T. O'Connor, and A. Kleyner, Practical Reliability Engineering (fifth edition). New York, USA: Wiley, 2012.

AGEING OF POWER ELECTRONICS IN NNP SAFETY SYSTEMS INCLUDING RECTIFIERS AND UPS SYSTEMS

Different aspects impacting ageing of power electronics are evaluated in the Nordic NPP context. It is concluded that the main aspect impacting ageing in the NPPs are impacts from the electrical grid. Different topologies of the rectifier system (e.g. thyristor-based vs transistor-based) have different characteristics and ability to withstand impact from surge voltage and voltage amplitude variations. Transistor-based rectifier achieves better operation performance (e.g. lower output voltage ripple and higher power factor), which leads to lower ripple current and less degradation of the batteries to be charged. The thyristor-based rectifier, on the other hand, has higher overcurrent capability from the power semiconductor perspective.

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