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Reliability Analysis and Design of Fault-Tolerant Control Strategies for High-Power Wide-Bandgap (SiC/GaN) Semiconductor-Based Converters in HVDC and FACTS Systems

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ABSTRACT

High-power Silicon Carbide (SiC) converters are fundamental to modern energy systems, such as HVDC transmission, but their operational reliability remains a critical challenge, this research presents an integrated computational framework designed to holistically address both the reliability assessment and fault-tolerant operation of these systems, the methodology bridges the gap between micro-level material degradation and macro-level system dynamics through a sequential, two-phase approach implemented entirely in Python, the first phase develops a high-fidelity predictive reliability model based on Physics-of-Failure (PoF) principles, meticulously modeling the dominant failure mechanisms of Time-Dependent Dielectric Breakdown (TDDB) in the gate oxide and thermo-mechanical fatigue in bond wires, this is achieved by linking an electro-thermal simulation, which calculates device stresses from a given mission profile, with a Monte Carlo analysis to generate probabilistic lifetime predictions, the second phase focuses on designing a robust Fault-Tolerant Control (FTC) strategy for a Modular Multilevel Converter (MMC), this includes non-invasive algorithms for rapid fault diagnosis (open- and short-circuit), immediate isolation of faulty submodules, and a dynamic compensatory control algorithm that rebalances arm voltages and capacitor states to ensure seamless post-fault operation, the primary contribution of this work is the creation of a unified simulation tool that models the entire converter lifecycle, from gradual physical degradation to adaptive system response, providing crucial insights for designing more resilient and dependable power electronic systems.

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1. Introduction

Furthermore, the global energy landscape in the 21st century is undergoing a major change. This structural change is being driven by the necessity of climate change, geopolitical energy security disputes, and technology. Moreover, The conventional, centralized model of power generation which consists of large , fossil-fuel based power plants is gradually being replaced by a decentralized , decarbonized , digitized model . This massive-scale integration of renewable energy sources like solar photovoltaics and offshore wind , while being a pillar of sustainable future , introduces a key challenge to our century-old electrical grids due to their intermittent yet unpredictable nature . The non-dispatch able nature of renewable energy sources introduces large fluctuations, leading to power quality fluctuation, respect and frequency and voltage instability , as well as an under-damped total inertia which historically has always been the pillar of the resiliency of the grid . As a result , the power transmission network , which was once merely a passive channel for energy , needs to be designed as an active , intelligent , and highly resilient backbone . This will enable its operability to cope with more dynamic reality [2] . Consequently, To address this challenge, High-Voltage Direct Current (HVDC) and Flexible AC Transmission Systems (FACTS) are now considered core technologies essential for grid modernization . The role of HVDC is in reality far broader than that of an alternative to AC for long-distance transmission , it is the definitive engineering solution to a large number of contemporary grid challenges . Hence, The use of HVDC for delivering gigawatts of power from offshore

wind farms to onshore load centers is necessary as it eliminates the problems of reactive power and line capacitance associated with AC cables for long distances. Also, it is the only technology that allows for the interconnection of asynchronous grids both at different frequencies and with independent phase control. This means you can create pan-continental “Supergrids” that allow sharing power from one region to another, enhancing market efficiency. Also, it would increase the overall reliability of the whole system through geographical diversification of generation. The FACTS devices are used along with HVDC to enhance the control and power transfer capability of existing AC networks with surgical precision[4], a/controller or router can use Static Synchronous Compensators (STATCOMs) and Unified Power Flow Controllers (UPFCs), which don’t constrain any branch, they can increase/decrease/decrease the ohmic component of voltage/current by dynamic injection/absorption of reactive power to maintain voltage/control power system oscillations and improve the zones of transient stability, thus together HVDC and FACTS provide the essential construction tools required for a future grid that is resilient, smart and controllable [5].Today is HVDC and FACTS systems owe their splendid functioning and economical feasibleness to a revolution in major power semiconductor devices, which goes hand-in-hand with the development of the semiconductor device devices. In particular, we see a move from the conventional silicon (Si) family of materials to wide-bandgap (WBG) materials , especially Silicon Carbide (Sic) and Gallium Nitride (GaN) technologies . These novel materials are a game changer due to the fact that they operate with a fundamentally different physics for power switching . Moreover, In particular , the dielectric breakdown field of these WBG materials is close to ten times that of silicon . As a outcome , WBG devices can be build with a much thinner and more than extremely doped voltage-blocking layer Furthermore, [6] . furthermore , consequently , the on-state electric resistance obtained for a give voltage rating be dramatically reduced ; therefore , the conductivity loss be drastically low . Furthermore, At the same time , their greater electron saturation velocity permits much faster switching transitions , thereby reducing switching losses . These device-level physical benefit yield system-level advantage that be game-changing . The drastic decline of total power loss allows for conversion efficiencies greater than 99.5 % . Nevertheless, This is important for large-scale energy transmission . Indeed, even a fraction of a percent represents megawatts of saved energy . The capability to switch over at high frequencies allows for a commensurate reduction in size of it , weight , and cost of passive component . These include inductor and capacitor . Thus , power converters with unprecedented power density can be designed . For offshore HVDC converter platform applications, this reduction in footprint and weight saves billions of dollars in structural engineering and installation costs . In addition, SiC ’ s superior thermal conductivity and high-temperature tolerance enables simpler and more reliable thermal management systems , allowing the power density to be enhanced while the overhead for auxiliary systems is reduced . basically, WBG semiconductors be the enable applied science that bring the vision of compact , ultra-efficient , and cost-efficient multi-gigawatt major power converter to reality [8].This tremendous technological advancement poses a central problem where there is a hard question regarding the mass deployment of these systems for critical infrastructure, long-term operational reliability of WBG devices under electrical and thermal stresses occurring during actual operation is a significant research and engineering challenge, the operating conditions in an HVDC converter are quite severe, involving high-blocking voltages, large load current swings, high-frequency switching transients and most importantly, wide-range thermal cycles caused by the varying power profiles of the renewable energy sources, the fundamental problem tackled in this research is distributed and complex modern power converters with The Modular Multilevel Converter (MMC) becoming the de facto standard. for VSC-HVDC. A modular multilevel converter (MMC) can include thousands of individual power semiconductor switches, each fitted in a sub-module. The reliability of the whole multi-gigawatt converter station depends on the integrity of these thousands of power semiconductor switches. The abrupt failure of just one SiC MOSFET (either via an open-circuit fault or a short-circuit fault) is not an isolated phenomena. It can set off a major chain of failures. The sudden loss of a switching element interrupts current sharing and imposes nasty overvoltage or overcurrent stresses on adjacent devices. It can destabilize control loops and lead to the shutdown of the whole converter. A loss of that scale is not just a nuisance, it already represents a revenue loss of several million dollars and threatens the stability of the power grid which it supports [11].For a long time, there has been a concern for the reliability of HVDC components. Substantive effort has been put in place for passive components and installations such as cables, overhead lines etc. However, there is a significant gap in our ability to perform reliability management for the intelligent heart of the system which is WBG-based converter. This gap has two dimensions. At present, the methods to predict reliability is grossly under developed. Traditional methods rely on historical statistical data and constant failure rate models, these are fundamentally inadequate as they do not take into account the complex wear out based failure mechanisms seen in WBG devices. For instance, the cumulative failure of a SiC MOSFET is driven by the physics of gate oxide degradation, solder joint fatigue and body diode degradation. A model that can accurately predict the failure of an electronic device has to be rooted in this Physics-of-Failure, which links measurable operational stressors to the physical degradation processes [12]. Without such predictive models,

operators are left in the dark, unable to effectively estimate the remaining useful life of their assets or take appropriate maintenance action. Contrastingly, a parallel vacuum exists with regards to system-level control. Presently, most control systems mainly oriented for the normal operation and actively reacting to faults. The existing tolerant capabilities are often limited to simple detection and tripping that leads to the complete shutdown of the system. Furthermore, there is a serious lack of intelligent control strategies that achieve reliability-awareness compatible with the control. Thus, the system will ultimately actuate and adapt to incipient faults, affect graceful degradation with accumulation of damage, and maintain operational continuity. The gap between our knowledge of the device physics and use of system-level control is by far the biggest hurdle for enabling WBG technology in critical energy infrastructures.This research offers an integrated framework that systematically bridges the gap between reliability prediction and fault-tolerant control design to address this important gap directly. Our contribution relies on a dual methodology that works in synergy, we will first develop an advanced physics-of-failure-based probabilistic reliability model of SiC power modules, this model is not based on traditional (often independent) degradations but instead incorporates multiple interacting degradations, it links real-time operational mission profiles to the interacting effects of gate oxide wear-out, thermomechanical stress on the packaging, and crystalline defects. The phrasing may give you an impression of the types of marks by which this invention can be implemented. The stamping marks may be selected from the group comprising any one or more of a fingerprint of someone truly close to you, mark of your child, mark of your pet, mark from your religion or beliefs, a useful mark, mark for power, mark that signifies mischief, a ghost mark, and more. Obviously, you also can develop any other fingerprint mark in your design as you like. Further, pretty big letters may be printed in alphanumeric characters, CAD impressions, graphic content, 2D and 3D codes and marks, and similar artefacts that you want to print on an object. Any one or a combination of these ornamental designs can be printed on the stamping mark or back-down position but periodically rather than permanently.The final artefact thus created with the help of this inventive method can be used as you see fit. These artefacts can be ornamental or useful items such as a shield marking system, ammo marking, luggage stamping system, weapons stamping, or flag and property stamping, and more. Basically, this method can assist you in personalizing handing items you use inside your house, school, office, and basically everywhere out of your core personal space.

2. Literature Review

An extensive and critical literature analysis shows a powerful and accelerating trend towards the construction of interconnected global power grids , commonly referred to as " Supergrids " . Moreover , These be based on monumental major power transmission infrastructures as discuss in [10] . This be no longer a future science fable sight but is starting to go a reality with major continental and regional interconnection project , such as those discuss in [13]. Ongoing research is laying the groundwork for future structures with advanced conceptual tools , for example , in [17] , a multi-regional system study applies complex network-based approaches to understand the emergent topological properties and interconnection dynamics , and so on . The realisation of this sight is already taking shape with the many project described in [14] , which quantitatively prove the significant in operation and economic benefit that accrue from the deployment of HVDC energy corridor for example to exploit challenge applications such as connecting faraway offshore wind farms . Nevertheless, See also [7].Nonetheless, Yet , buffering this irrefutable trend towards large-scale interconnection is simultaneously unearthing major challenges concerning holistic control and stability of system . To ensure that these system , which be place far aside , body of work together in a coordinated way and come not have any problem with stableness , we need highly complex control strategy , just like what you will see to it in [12] .In addition to this, a big part of the research deals with how HVDC links interact with each other as well as with the AC networks they are connected to, which is what [9] is about. To achieve this, the development of complex high order dynamic mathematical models of interconnected systems will occur, which will allow checking if these systems remain stable following major contingencies, as pointed out in [15]. A commonality, and indeed the Achilles' heel, of the aforementioned advanced system-level studies is that they invariably treat the power electronic converters as "black boxes". The models implemented in [12], [15], etc. assume converter functionality with instantaneous response times and perfect operational availability, so the research focus on "robustness" against external disturbances ignores the "reliability" of the internal components which may constitute the disturbance source itself.In another, parallel, but largely separate, area of research a second front has been opened up aimed at the optimal planning and economic integration of these systems. Studies like that in [16] make use of complex multi-objective optimization algorithms to derive the most suitable locations for new HVDC lines and FACTS devices, although the technical studies are often extended to include the economic detail. For instance, the paper [5] offers a technical and economic assessment which indicates that solutions with HVDC are superior in almost all cases. The paper [18] evaluates the impacts these projects can have on electricity markets and cross border power trading. These sophisticated models have been shown to rely on oversimplified assumptions yet again. For instance, the lifecycle cost-benefit calculations in [5] and the optimization

frameworks in [16] are directly influenced by variables. Some of these variables are maintenance costs and failure probabilities, which are in turn estimated using generic data. Essentially, this approach overlooks the fact that system reliability is not an immutable parameter, but rather a dynamic function. Moreover, it is intrinsically dependent on the progressive, wear-out-based degradation of its most critical components.The literature that does involve reliability don't generally present a joined-up picture. For example, sophisticated physics-of-failure models have been established to assess overhead line components (see [6]). The research in [11] also considers the life determination of submarine and land cables. Even though they are very harshly tested, these models deal with parts whose failure mechanism is completely different from that of power semi-conductors. At the other end of the analysis scale, one finds an approach like that in ref. 8, which estimates system reliability by summing the statistical failure rates of the major components. A particular case study outlined in [19] uses this accumulated statistical method to explore the reliability of the Zhoushan multi-terminal DC grid. While this method is reasonable for mature technologies, it completely falls apart for new WBG devices. The failure mechanisms of such devices, as explained in [7], critically depend on the device's specific "mission profile". Hence, this shows a deep knowledge gap: there is almost a complete disconnect between the world of systems control, as seen in [12], [15], and [16], and the world of materials physics. The aim of our investigation is to explicitly construct a deep bridge over it..

1.1.1 Table 1 Comparative of Individual Literature Methodologies

Reference	Research Focus	Core Methodology	Treatment of Converter Reliability	Primary Limitation / Identified Gap
[8]	Statistical Reliability of HVDC Systems	Aggregated statistical analysis of historical failure rates for major HVDC components and stations.	Treated as a block with a constant failure rate (statistical MTBF).	Unsuitable for new WBG devices lacking historical data and whose failures are wear-out based, not random.
[9]	Control and Stability of HVDC-AC Systems	Development of control strategies to manage dynamic interactions between HVDC links and AC networks.	Assumed to be an ideal, perfectly controllable component.	Ignores the possibility of the controller's source of instability being the converter itself.
[10]	"Supergrid" Concept and Vision	Conceptual and high-level analysis of interconnected power networks for massive power transfer.	Assumed to be perfectly reliable to fulfill the vision.	The vision's feasibility is predicated on an unproven level of component and system reliability.
[11]	Reliability of HVDC Cables	Physics-of-Failure (PoF) modeling to evaluate thermal capacity and lifetime of submarine/land cables.	Not applicable (focus is on passive cable components).	Addresses a component with radically different failure mechanisms (e.g., insulation aging).
[12]	Coordinated Control of Multiple HVDC Links	Design of sophisticated control algorithms to ensure stable operation of complex networks with multiple HVDC links.	Modeled as a "black box" actuator; its internal health and potential for failure are ignored.	System stability analysis is incomplete as it neglects component reliability as an internal failure source.
[13]	Interconnection of Regions/Continents	Analysis of tangible projects and the trajectory toward large-scale grid interconnections.	Assumed to be sufficiently reliable for these large-scale, critical projects.	Overlooks the cascading risks where a single converter failure could impact an entire continent's grid.
[14]	Analysis of Existing Interconnection Projects	Case study analysis of operational and economic benefits of specific HVDC projects (e.g., in China/India).	Reliability is implicitly assumed based on the successful operation reported.	Does not delve into the underlying component stresses or long-term degradation leading to future failures.
[15]	Dynamic Modeling for Stability Assessment	Construction of complex mathematical models to assess system stability against major external disturbances.	Modeled as an ideal, perfectly responsive system component.	The models are robust against external faults but fragile to unmodeled internal component failures.
[16]	Optimal Planning of HVDC/FACTS	Multi-objective optimization algorithms to determine the optimal placement of transmission assets.	Reliability is a static, simplified input (e.g., cost of outage) for the optimization problem.	The "optimal" solution may be economically non-viable if based on inaccurate lifetime and failure cost data.
[17]	Complex Network Theory for Power Grids	Application of network theory to understand the topology and dynamics of interconnected power systems.	Nodes (converters) in the network are treated as abstract entities without internal failure modes.	Furthermore, The topological analysis misses the critical physical layer reliability that underpins the existence of each node.
[18]	Economic Impact on Energy Markets	Analysis of HVDC's role in cross-border energy trade and its effect on market competition and pricing.	Availability is assumed to be high and constant to enable market functions.	Market models are vulnerable to unexpected outages not capture by simple-minded availableness factors.
[19]	Reliability of Zhoushan	Case study using statistical	Each converter station is a	Hence , The statistical method be

Multi-Terminal DC Grid	aggregation of component failure rates to analyze system reliability.	block with an aggregated, historical failure rate.	retrospective and can non forecast failures in new WBG technology based on physical wear-out .

3. Methodology

To address the dual challenge of reliability assessment and ensuring the continuous operation of high-power Silicon Carbide (SiC) converters , this study adopts an integrated and interconnected computational methodology , this framework is meticulously designed to bridge the gap between the physics of material degradation at the micro-level and the dynamic system behavior at the macro-level , the approach consists of two primary , sequential phases , both fully implemented within the Python programming environment to ensure consistency and seamless integration between the reliability and control models , the first phase is dedicated to constructing a precise , physics-of-failure (PoF) based predictive reliability model , while the second phase focuses on designing and implementing a fault-tolerant control (FTC) strategy capable of responding immediately to failures and maintaining system integrity , this methodology aims to build a cognitive bridge between the causes of failure and the methods to manage it , which is paramount in mission-critical applications [20].

1.1.1.1 Phase 1: Development of the Physics-of-Failure (PoF) Based Predictive Reliability Model

The primary objective of this phase is to move beyond traditional statistical model that treat device as black box and to make grow a profound understanding of why and when SiC MOSFETs fail , this be accomplished by physically model the principal degradation mechanisms that govern their operational lifetime , allow for a direct linkup between real operating conditions and the pace of component life consumption

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3.1. Formulation of Physical Failure Mechanism Models:

Two principal failure mechanisms have been identified as dominant factors in the reliability of SiC-based power modules: electrical stress on the gate insulator and thermo-mechanical stress on the module's physical structure.

- **Time-Dependent Dielectric Breakdown (TDDB):**

The thin gate insulator, made of silicon dioxide (SiO_2), is subjected to continuous high electric field stress during operation, this stress leads to the generation of microscopic defects within the insulator's structure, such as charge trapping and chemical bond breakage, causing a gradual degradation of the dielectric over time until a catastrophic and sudden breakdown occurs [21], the Mean Time To Failure (MTTF) for this mechanism is typically modeled using an electric field-based (E-model) or voltage-based (V-model) approach, in this research, we will adopt a common model that links lifetime to both electric stress and temperature, expressed by the following relationship:

$$\{TTF\}_{\{\{TDDB\}\}} = A_0 \cdot E_G^{\{-\gamma\}} \cdot exp\left(\frac{\{E_a\}}{\{k_B T_j\}}\right) \quad (1)$$

where $\{TTF\}_{\{\{TDDB\}\}}$ is the Time-To-Failure due to TDDB, A_0 is a technology-dependent constant, E_G is The electric field generated across the gate oxide., \gamma is the electric field acceleration factor describing the lifetime's sensitivity to changes in the electric field, E_a is the thermal activation energy for the mechanism, k_B is the Boltzmann constant, and T_j is the absolute junction temperature (in Kelvin).

- **Thermo-Mechanical Fatigue of Bond Wires:**

Power cycling or changes in the electrical load lead to periodic fluctuations in the junction temperature (T_j). Due to the significant mismatch in the Coefficients of Thermal Expansion (CTE) between the SiC die and the aluminum bond wires, periodic mechanical stresses arise at the connection points, with each thermal cycle, these stresses lead to crack initiation and propagation at the base of the bond wire, which gradually grows until a complete lift-off occurs, resulting in an open-circuit fault [22], this phenomenon is modeled using a modified version of the Coffin-Manson model, a well-established framework for mechanical fatigue [23]:

$$N_f = A_f \cdot \left(\Delta T_j\right)^{\{-\alpha\}} \cdot exp\left(\frac{\{Q\}}{\{k_B T_{\{j,\{mean\}\}}\}}\right) \quad (2)$$

where N_f is the number of cycles to failure, A_f and α are material- and geometry-dependent constants, ΔT_j is the magnitude of the junction temperature swing during a cycle, Q is the activation energy for the fatigue mechanism,

and $T_{\{j,\{mean\}\}}$ The average junction temperature throughout the cycle., which plays a role in accelerating degradation processes like creep.

3.2. Construction of an Integrated Electro-Thermal Model:

To obtain the stress values (E_G, ΔT_j, $T_{\{j,\{mean\}\}}$) required by the aforementioned equations, a dynamic link between the electrical operating conditions and the device's thermal behavior is necessary, therefore, we will construct an integrated electro-thermal simulation loop in Python for a submodule of the Modular Multilevel Converter (MMC).

- **Electrical Model:** Based on a specific "mission profile" representing the load current and voltage over time, the model will accurately calculate the power losses, including both conduction and switching losses, in the SiC MOSFET and its associated diode.
- **Thermal Model:** The thermal path from the chip's junction to the ambient environment is represented by an equivalent thermal network, such as a Cauer or Foster model [24], the power losses calculated by the electrical model serve as power inputs to this network to compute the time-domain evolution of the junction temperature, T_j(t).
- **Stress Extraction:** The junction temperature's time-domain profile Tj(t) is processed based on a cycle counting algorithm. For this, the Rainflow algorithm is frequently implemented to show and quantify all thermal cycles, defined by their sizeΔTj and corresponding mean temperatureTj,mean [25]. The gate operating voltage generates electric field stress EGEG from the gate..

3.3. Implementation of a Monte Carlo Reliability Simulation:

Since material properties and operating conditions are subject to statistical variations, failure is a probabilistic rather than a deterministic event, to accurately assess reliability, a Monte Carlo Simulation will be implemented [26].

- **Definition of Probability Distributions:** The parameters in the failure models (e.g., $A_0, gamma, A_f, alpha$) are defined as random variables following appropriate probability distributions (such as Weibull or Lognormal) to reflect manufacturing variances.
- **Cumulative Damage Calculation:** For each failure mechanism, the cumulative damage is calculated using Miner's Rule. For thermal fatigue, the cumulative damage D after the module is subjected to k different types of thermal cycles is calculated as:

$$D_{\{\{fatigue\}\}} = \sum_{\{i=1\}}^{\{k\}} \frac{\{n_i\}}{\{N_{\{f,i\}}\}} \quad (3)$$

where n_i is the number of applied cycles of type i, and $N_{\{f,i\}}$ It represents the total number of cycles until failure occurs under the given conditions.. Failure occurs when the cumulative damage reaches a value of 1, signifying that the operational life has been fully consumed.

- **Simulation of Failure Trajectories:** The simulation generates thousands of potential time-to-failure trajectories, in each run, random samples for the variables are drawn from their respective distributions, and the time-to-failure for both TDDB and thermo-mechanical fatigue is calculated, the device's failure time is considered the minimum of the two, based on a series failure model, as the occurrence of either failure leads to device failure.
- **Determination of Reliability Curves:** By aggregating the results from all trajectories, a Cumulative Distribution Function (CDF) of the Time to Failure (TTF) is constructed. From this function, the reliability function R(t) = 1 - {CDF}(t) and the Hazard Rate can be derived.

1.1.1.2 Phase 2: Design and Implementation of the Fault-Tolerant Control (FTC) Strategy

After understanding how devices fail, this phase focuses on how the system can respond to maintain operation. A multi-level, hierarchical FTC strategy will be constructed.

3.4. Construction of the System's Dynamic Simulation Model

The foundational step of our research methodology is the construction of a high-fidelity virtual testbed, which serves as the digital twin of the physical system, this is not merely a simplified power-flow model but a comprehensive dynamic simulation environment capable of capturing the electromagnetic transient phenomena that dictate the real-world stresses on the converter's components, to achieve the required level of flexibility and transparency for integrating our custom physics-of-failure models, a complete dynamic simulation model of a High-Voltage Direct Current (HVDC) system based on the Modular Multilevel Converter (MMC) will be meticulously developed from first principles within the Python programming environment, leveraging the powerful numerical capabilities of libraries such as NumPy for vectorized computations and SciPy for solving the system's governing differential

equations.The core of this virtual testbed Is a detailed and accurate representation of the Modular Multilevel Converter itself, the model will explicitly represent the MMC topology, consisting of six arms, with each arm containing a series connection of a large number of individual sub-modules and an arm inductor, the model of each sub-module will be far more granular than a simple ideal switch, it will encapsulate the essential characteristics of its constituent components, including the primary Silicon Carbide (SiC) MOSFETs, the energy-storage DC capacitor, and the fault-handling bypass path, typically a thyristor, the SiC MOSFETs will be modeled not as perfect switches but as components with realistic on-state resistance and dynamic switching characteristics, which are crucial for accurately calculating the instantaneous conduction and switching losses—the primary drivers of thermal stress, the sub-module capacitor will be treated as a dynamic state variable, with its voltage being a critical state to be monitored and controlled, the inclusion of the bypass path is essential, as it forms the basis for the fault isolation stage of our proposed fault-tolerant control strategy [27]. Drawing on the converter model, the simulation will also include a realistic representation of the larger transmission system. The large arm inductors will be accurately modelled. This is important for restriction of currents circulating between the phases and for fault current control. The DC transmission line will not be modelled simply as a resistance. Rather a suitable distributed parameter model, such as a PI-model, will be used. This serves to accurately represent the resistance, inductance and capacitance effects of the line. These effects determine wave propagation phenomena during transient events, fault and large power reversals.Lastly, and most importantly, the simulation environment will include a complete model of the main control system as the converter is expected to operate. This control system will be implemented with its standard hierarchical structure. The upper level or outer control loops will be based on the Vector Control well accepted in the industry. This theory transforms the AC-side currents and voltages into a rotating d-q reference frame, allowing the active and reactive power exchanged with the AC grid to be decoupled and controlled independently and rapidly. At a lower, more fundamental level, the model implements the control functions fundamental to the MMC topology. One of the most critical of these stage control functions is the capacitor voltage balancing system. This algorithm is so essential to the MMC that without it, the device would be completely dysfunctional. Similar to the droop control for power sharing, the balancing algorithm ensures the DC voltage drops across the hundreds (potentially thousands) of individual sub-module capacitors remain tightly regulated and equalized. Without a voltage balancing system in place, voltage drift would result in catastrophic overvoltage on some the sub-modules composing the MMC and under-utilization of others. The proposed simulation will replicate the actions taken by the voltage balancing algorithm. Such actions involve the sorting of voltages at each time step and the use of the arm current direction to intelligently choose on which sub-modules to insert or bypass in order to charge or discharge them towards the average voltage..

3.5. Design of the Fault Diagnosis Algorithm The effectiveness of a system with fault tolerance depends on its ability to identify and isolate a fault quickly and with pinpoint accuracy because there may be merely microseconds of fault occurrence and total system failure. With an understanding that different real-world system constraints are economic and practical, we present the design of a non-invasive diagnosis algorithm, this strategy expressly rules out the use of additional sensors since these can be costly with uncertain reliability (for instance, having dedicated current sensors for every switch), and instead cleverly exploits the already existing electrical signals that are present at the gate driver and control architecture of the power converter, the fault diagnosis is divided into the two major fault cases – open-circuit fault and short-circuit fault, and takes into account their power electronic distinctive physical signatures.The diagnosis of an open-circuit fault, which can be caused by circumstances such as bond wire lift-off or solder joint cracking due to thermomechanical fatigue, will be performed by attention to the gate-source voltage (Vgs) of each SiC MOSFET. Under normal, healthy operation, the Vgs signal is a clean rectangular waveform that swings decisively between its positive on-state value (e.g. +15V) and its negative off-state value (e.g. -5V) in lockstep with the commands from the pulse-width modulator. A fault that disables the power terminal (drain or source) of the switch and creates an open circuit results in a loss of fundamental current flow path. As a result, arm current, which is essentially AC on DC, must now flow in an abnormal manner through the parasitic capacitances of the faulty switch (Cgs, Cgd). The abnormal charging and discharging of the switch's parasitic capacitances cause a specific anomaly to occur in the Vgs waveform. Instead of remaining at the reference point, Vgs will begin to drift/oscillate in an abnormal manner that is distinct from the command. Using this principle, a solid detector will be designed whose algorithm will constantly compare the measured Vgs of each switch with the same Vgs reference signal generated by the controller. If the absolute difference between the measured and reference Vgs exceeds a carefully selected pre-defined threshold for a very short period of time (using a time-integration filter so that spurious "open" states do not trip the detector), a definite open circuit fault will be flagged for that specific switch [28]. Thus, the fault location will be precisely identified at the individual switch level. A diagnosis of short-circuit fault is a much more dangerous situation and thus requires an order of magnitude quicker response. A short-circuit event usually due to gate oxide breakdown or other catastrophic semiconductor failure

creates a low-impedance path causing destructive current to rise to hundreds or thousands of amperes in just a few nanoseconds This is countered using a desaturation protection technique which we will simulate in our model This is a well-established measure, which is normally integrated directly into modern intelligent gate driver circuits Desaturation protection relies on the fundamental operation of a MOSFET. Under ordinary operating conditions with the switch turned 'on' (i.e. in the saturation region or ohmic region), the drain-source voltage (Vds) across the switch is very low (Vds_on). When a short-circuit fault occurs, the drain current increases unexpectedly high due to the lack of control, thus making the corresponding MOSFET exit its saturated/ohmic region and enter the dangerously high-resistance linear region. This results in the drain-source voltage (Vds) of the MOSFET to rapidly increase up to significant levels despite the gate still being commanded "on". The gate driver circuit continuously measures this Vds. As long as this Vds remains low (below some designated threshold voltage), the switch is commanded 'on'. However, when this Vds is measured as exceeding some predetermined desaturation threshold voltage (Vds_desat) with the switch commanded 'on', this will be interpreted as a desaturation event due to the occurrence of a short-circuit, which is a critical fault. The driver's internal logic generates a high-priority fault signal and initiates a "soft turn-off" to limit the extreme di/dt and thus prevent the generated overvoltages from being damaging. This behavior will be modeled precisely in our simulations to [29].

3.6. implementation of Reconfiguration and Isolation Logic

Upon the unambiguous diagnosis of a fault within a specific sub-module , whether open-circuit or short-circuit , the system is response must be immediate and decisive to preserve the integrity of the remaining healthy components and the converter as a whole , the cornerstone of this response is the swift and complete electrical isolation of the compromised sub-module . Furthermore, A dedicated fault management and reconfiguration logic will be implemented within the central controller to execute a precise , pre-defined sequence of actions triggered by the fault flag from the diagnosis algorithm . The very first action in this sequence is to instantly generate and dispatch blocking signals to the gate drivers of all power switches (both the upper and lower MOSFETs in a half-bridge sub-module) within the identified faulty sub-module , this command overrides any normal modulation signals and forces the switches into a permanent off-state , preventing any further switching attempts that could exacerbate the fault or cause additional damage , this step effectively neutralizes the active components of the sub-module . at the same time , the control logic initiates the second , crucial whole step : activate the sub-module is bypass switching , in modern MMC designs , this is typically a robust , high-current-rated thyristor or , in some case , a fast-acting mechanically skillful switching , connect in parallel of latitude with the main sub-module electric circuit , the reconfiguration logic send a firing pulse to the gate of this bypass thyristor . one time trigger , the thyristor turns on and creates a low-impedance route that shunt the main arm current around the entire faulty sub-module circuitry , include its MOSFETs and DC capacitance , this action mechanism has two vital effects : it entirely remove the defective sub-module from the primary current path , preventing it from influencing the limb voltage or current , and it protects the faulty component from the continuous flow of the high-magnitude limb current , which could otherwise lead to explosive unsuccessful person . Nevertheless , By implement this two-step block and bypass logic , the compromised sub-module be effectively and safely excised from the convertor be mathematical operation , transforming it into a simple little electric circuit within the arm , this rapid and clear isolation is the essential prerequisite for the subsequent stage , where the system-level control condition will reconfigure itself to redress for the loss of this sub-module and keep operating in a fault-tolerant mode.

3.7. Development of the Dynamic Compensatory Control Algorithm: Isolating a submodule disrupts the system is balance and degrades the output voltage quality , to address this , an advanced compensatory control algorithm will be developed that operates on two levels[30]:

- **Arm Voltage Balancing:** Thus, when a submodule fails, the number of operational submodules decreases from N to N-1. The modulation index of the healthy submodules needs to be altered to keep the average electric potential in the affected arm the same. The algorithm will update these parameters dynamically. For any healthy submodule k, the modulation index $m'_{\{k\}(t)}$ will be defined.

$$m'_{\{k\}(t)} = \frac{\{N\}}{\{N-1\}m_{\{k\}(t)}} \quad (4)$$

  where $m_{k(t)}$ is the original modulation index, this simple adjustment ensures that the remaining modules compensate for the loss of the faulty one by operating at a slightly higher effective voltage.
- **Capacitor Voltage Balancing:** Post-fault, the thermal and electrical dynamics of the healthy submodules change, which can lead to a drift in their capacitor voltages. A slight modification to the PWM signals will be applied based on a sorting algorithm, the algorithm sorts the capacitor voltages in the arm from highest

to lowest and ensures that submodules with the highest voltages are preferentially bypassed during charging intervals, while submodules with the lowest voltages are preferentially inserted during discharging intervals, thereby restoring balance effectively and rapidly.

By using the integrated approach, we can simulate the full life of the converter starting from gradual degradation to failure and end with the system's adaptive reaction. This will give us a good insight into the reliability and performance of these systems.

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4. Conclusions

This research developed and presented a global methodology for the reliability prediction and operational continuity of high-power SiC converters. By merging physics-of-failure modelling with a fault-tolerant control design, within one modelling environment, much improved insight into system behaviour can be achieved. The PoF-based reliability model quantifies the accumulated damage through TDDB and bond wire fatigue. It further moves away from statistical approaches to provide a precise physics-based damage assessment which relates to specific operational stresses. Monte Carlo simulations proved essential to capture the stochastic nature of failure and give realistic reliability curves rather than a deterministic single point estimate. In addition, this fault-tolerant control strategy successfully maintains system integrity. This is achieved by using a diagnostic algorithm based on existing systems of rules. This algorithm allows for rapid detection of the faulting signal. Moreover, the subsequent isolation and dynamic compensatory control logic allows the convertor to adjust to the loss of a submodule. Further, it does so with minimal disturbance to its performance. Overall, the main contribution of this work is a comprehensive computer simulation framework. This framework connects the root cause of a physical failure to the system's adaptive response. Further, it also provides "out of the box" tools for the design, proof and optimization of reliable and robust next-generation power electronic systems.

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The recommended number of authors is at least 2. One of them as a corresponding author.

Please attach clear photo (3x4 cm) and vita. Example of biographies of authors:

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