# D4.1. FAULT TOLERANT CONTROL OF SIC/GAN POWER CONVERTERS

## Reinventing High-performance pOwer converters for heavy-Duty electric trAnSport

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## DISCLAIMER

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# EXECUTIVE SUMMARY

This document describes fault-tolerant control strategies for the SiC/GaN power converter and the eMotor of the RHODaS IMD. It outlines control levels within the proposed IMD, details fast response strategies for critical faults managed by the power converter control and defines fault-tolerant control to be implemented by cloud/edge computing for the IMD. The document also addresses potential faults in the power converter and electric motor, discussing feasible fault detection strategies.

The document examines the integrated sensors in the system clarifying their functions and the flow of information. Proposed algorithms for fault detection and localization are presented, explaining operational mechanisms and precision. Additionally, the document elaborates on two power converter fault-tolerance algorithms: a derating algorithm and an operating mode change algorithm.

In summary, the document provides a comprehensive overview of fault-tolerant control in power converters and IMD, covering various aspects from fault types, sensor networks and algorithmic strategies.

## LIST OF ACRONYMS

| Acronyms | Definition |
|---|---|
| ABS | Absolute |
| AC | Alternating Current |
| ADC | Analog-to-Digital Converter |
| AI | Artificial Intelligence |
| ANN | Artificial Neural Network |
| API | Application Programming Interface |
| CAN | Controller area network |
| CPU | Central processing Unit |
| DC | Direct Current |
| DSS | Decision Support System |
| $\varepsilon$ | Threshold |
| ECU | Electronic Control Unit |
| EM | Electric Machine |
| eMOTOR | Electric Motor |
| FFT | Fast Fourier transform |
| FTC | Fault-tolerant control |
| GaN | Gallium Nitride |
| HMI | Human Machine Interface |
| I2C | Inter-Integrated Circuit |
| IMD | Integrated Motor Drive |
| IOT | Internet Of Things |
| MCSA | Motor Current Signature Analysis |
| ML | Machine Learning |
| MQTT | Message Queuing Telemetry Transport |
| NTC | Negative Temperature Coefficient |
| PM | Permanent Magnet |
| PSD | Power Spectrum Density |
| PWM | Pulse Width Modulation |
| RHODAS | Reinventing High-performance pOwer converters for heavy-Duty electric trAnSport |
| RPM | Revolution per minute |
| RST | Reset |
| SiC | Silicon Carbide |
| SPI | Serial Peripheral Interface |
| SVM | Support Vector Machine |
| $T_{cx}$ | Case temperature of transistor $x$ |
| THD | Total Harmonic Distortion |
| vCPU | Virtual Central Processing Unit |
| $V_H$ | Upper sub-bus voltage |
| $V_L$ | Lower sub-bus voltage |

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# 1 INTRODUCTION

## 1.1 DESCRIPTION OF THE DOCUMENT AND PURSUE

This report provides an exhaustive delineation of the fault-tolerant control system applied to the SiC-GaN T-type hybrid converter developed within the RHODaS project. Initially, the deliverable introduces the concept of fault-tolerant control and elaborates on the various levels of control within the proposed IMD. Then, diverse failure scenarios potentially manifesting in the power converter are comprehensively addressed, with meticulous detailing of their root causes and the potential impacts on the system. Furthermore, strategies for preventing these failures are discussed, identifying key parameters that require continuous monitoring to mitigate potential issues.

The report also includes a detailed analysis of the various sensors integrated into the system, explaining the functions that will be implemented based on the data acquired from these sensors.

Concluding the report, detailed insight is provided into the fault detection, localization and mitigation algorithms slated for implementation in the power converters and th eIMD system. These algorithms are intended to identify, locate and mitigate anomalies effectively, facilitating a swift and effective response to critical situations.

This deliverable will be updated at M29, coinciding with the advancement of the high-power converter design and the completion of testing for the fault detection, localization, and mitigation algorithms.

## 1.2 WPS AND TASKS RELATED WITH THE DELIVERABLE

This deliverable refers to Task 4.1 included in WP4: Software design and development of digital tools.

# 2 FAULT TOLERANT CONTROL FOR RHODaS POWERTRAIN

Fault-tolerant control (FTC) is a control strategy that aims to keep the closed-loop system stable when system components, sensors or actuators fail, maintaining predefined specific performance requirements, even lower than the system's nominal ones. In this way, FCT strategies contribute to increasing the resilience of the system against failures.

Naturally, the structure and objectives of the FTC depend on the plant to be controlled and the minimum acceptable specifications for it. In the case of the RHODAS project, the objective is to design a new high voltage (1000VDC minimum) and high power (150kW rated, 250 kW maximum) power inverter that can be integrated with an electric motor of at least 650Vrms phase to phase, coupling to a gearbox system.

In this system, if a critical fault occurs (short circuit, overvoltage...), the protections at the converter level will act, stopping the operation of the drive.

However, harsh drive operating conditions, mechanical wear, aging of components or poor manufacturing can cause some undesirable failures that are initially usually insignificant, but the severity of these failures can gradually increase and cause the failure of other components. A sudden catastrophic failure can even cause electric vehicle systems to stop working, creating serious safety risks. Therefore, a fault diagnosis adapted to the different operating modes of the powertrain and that detects different potential faults is necessary to guarantee the safety of the driver and the electric vehicle. Once the failure has been diagnosed, the fault-tolerant control strategy, if applicable, can mitigate the impact on the usability of the vehicle, and/or increase the operating safety levels under non-critical failures.

Therefore, and as previously described in Deliverable D2.1, a supervision and control network defined by three levels is deployed in RHODaS, each with its corresponding CPU, as a first step before developing and implementing FTC strategies:

- **Base control** (power inverter control CPU). The purpose of the inverter CPU is to control the torque and speed of the electric motor, through closed current and speed loops, and to supervise the operation of the inverter and the motor. This supervision aims to detect critical current, voltage, temperature and speed faults.

  In addition to the protection by exceeding threshold levels for these critical signals, the inverter CPU may include some data analysis algorithm to determine very rapidly evolving fault dynamics, which advise the implementation of immediate mitigation measures at the local level. For example, the transition from three to two levels can be established if the performance in delivered power exceeds the specifications of the three-level system (due to current limitation in the GaN materials), or excessive overheating of the GaN transistors is detected due to high currents maintained in time.

- **Local supervision** (IoT Gateway control CPU). The Gateway is responsible for connecting the plant information of the electric powertrain with the cloud applications. In addition, the CPU included in the Gateway controls the network of additional sensors defined in the RHODaS project, for local supervision of the powertrain. Specific vibration, temperature, current and voltage sensors and others can be connected to this network, which is responsible for collecting powertrain information for local monitoring.

  Fault extraction is also performed by this Gateway CPU, for example, through Fourier decomposition of motor currents or analysis of the total energy contained in the measurement of mechanical vibrations of the motor or gearboxes. In this way, and unlike the inverter CPU, which is responsible for instantaneous control and protection of the inverter and motor the Gateway CPU could establish local supervision and protection against rapid evolution of the fault through the analysis of local signals of broad spectrum and the extraction of fault features on them.

- **Remote supervision** (vCPU in the cloud). The virtual CPU running on the cloud server defined in RHODaS uses the information extracted from the plant (failure characteristics), stored in the cloud databases, for the execution of functions that require the use of massive data, but that have relatively long execution periods in time, for example, maintenance protocols for revision and substitution of equipment and powertrain components. The information transferred and stored in the cloud includes fault characteristics extracted from local information (fault features) by the plant CPUs (CPUs of Inverter and Gateway), such as the effective values of the current in the motor, the harmonic decomposition of these currents or the vibration profiles of the powertrain. This information, stored massively on the cloud, can be used to establish fault detection and identification systems, even predictively, or to manage the operation of vehicles in fleet control systems. For the development of these data- and model-based algorithms, AI and ML techniques can be widely used.

In this control and supervision structure, and apart from processing local data for protection issues, the equipment's' CPUs (inverter and motor and cooling systems) send data to the Gateway. The Gateway level oversees the consolidation and synchronization of these data, preparing it for transmission to the cloud. The Gateway will also be responsible for retrieving data from additional non-invasive sensors installed on the IMD powertrain and directly connected to the Gateway. This data acquisition contributes to condition monitoring and predictive maintenance of the system. Moreover, the Gateway executes signal processing algorithms to extract fault features (Fourier analysis, PSD…) and could perform additional fault detection not included into the Converter CPU (Fourier analysis, trends and fault featuring detections, …)

In the cloud level, data will be stored and processed by the IoT platform, in which Digital Twin runs. The Digital Twin will use the stored data to run models of the system to identify and predicts long term faults. A front-end application of the Decision Support System will also be available for remote access, as well as Predictive Maintenance through Condition Monitoring functions. Machine Learning (ML) based predictive models are developed based on the historical data from the sensors during normal and abnormal conditions of the powertrain, and the behaviour is continuously monitored with respect to current operating characteristics.

This control scheme is shown in Figure 3.1. In the figure, the various parameters which affect the performance of the power train, such as voltage, current, vibration, speed and motor position and temperatures are measured and captured by the sensor network, including inverter sensors for motor control. Accelerometer is used for finding the vibration of the motor and gearboxes. Current sensor, voltage sensor and speed sensor are used to measure current, voltage and speed of the PM motor. The values from the sensors are digitized, locally processed at the inverter and Gateway CPUs, and fault features obtained, sent and stored in the cloud for further processing.

Therefore, Fault Tolerant Control (FTC) to be implemented in RHODaS powertrain comprises two main parts: failure detection and fall-back strategy. Once performed the fault detection and identification, in any of the previous levels, FTC strategies can be established.

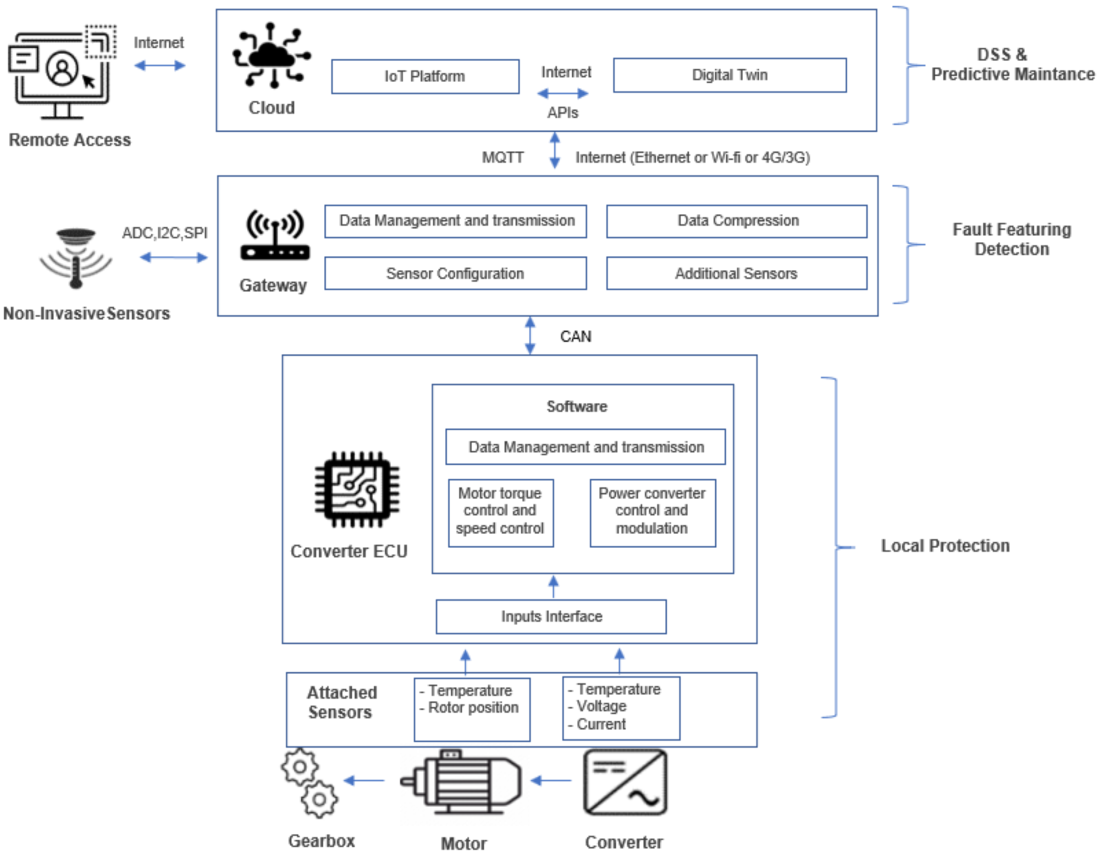


*Figure 2.1 Scheme of data control in the IMD.*

FTC solutions are divided into two classes: passive and active approaches. Passive methods are based on robust control techniques. Active approaches are based on fault adaptation and system reconfiguration. In RHODaS, an active fault-tolerant approach is applied by reorganizing the converter to adopt the best control topology (i.e., three-level or two-level voltages) and/or applying some derating in the power delivered depending on the available feedback and operating hardware.

The inherent redundancy provided by the three-level inverter is the key to the RHODaS fault-tolerant system. That is, operational problems in the inverter system can be mitigated either by reducing the operating ranges of the converter (i.e., voltages and power) if a failure appears in the SiC levels, or by changing from three to two levels in case of problems in the intermediate GaN sections of the converter (that is, increasing the THD while maintaining the high-power rates of the converter).

Furthermore, it is necessary to define a reconfiguration mechanism (transition strategy) for fault-tolerant control in the RHODaS powertrain system. The reconfiguration strategy, whose main objective is to ensure short and smooth transients when switching from one converter topology to another in case of fault detection, must be established through a converter switching control.

Before presenting the RHODaS powertrain FTC approaches, the following reviews and details the faults that can come from the power converter and the motor.

# 3 TYPES OF FAULTS IN WIDE-BANDGAP POWER CONVERTERS

During the operation of the power converter, various faults may manifest, thereby impacting the system's functionality. Some failures hold critical implications, requiring an immediate shut-down of converter and motor operations or even resulting in irreversible damage. Alternatively, other faults may compromise the converter's ability to function optimally, thereby increasing overall system losses or providing inaccurate data to the control system. Consequently, a comprehensive study is crucial to identify the types of failures that may arise in the power converter, assess their criticality, and ascertain potential resolution strategies. Specific failures have previously been introduced in detail in D2.1.

This section outlines the various faults that can appear in the power converter. It is crucial to underscore those failures within the control system itself are excluded from consideration, as any malfunction in this system could cascade into the converter failures detailed in this section.

The primary failures that may occur include:

- **Transistor Failure:** Transistors can be destroyed due to various factors, such as overvoltage, overcurrent, false switching, or excessive temperature. To mitigate the risk of transistor destruction, it is essential to monitor various parameters and take corrective action upon detecting any anomalous behaviour. Additionally, using drivers with protections can help minimize the likelihood of destruction caused by false switching.
- **DC Bus Breakdown**: The DC bus may experience breakdowns arising from overvoltages in its capacitors or imbalances between the positive and negative semi-buses in a three-level system. Therefore, it is imperative to monitor the DC bus voltages and balance the bus when necessary.
- **Overvoltage:** If the voltage withstanded by the transistor is excessive, the risk of breakage arises. This overvoltage can be attributed to a malfunction in the DC bus or the circuit's parasitic inductance, generating voltage spikes during switching, i.e., ringing. The converter should be designed to minimize the parasitic inductance of the power loop to mitigate this risk. Moreover, the control system should actively monitor and balance DC bus voltages.
- **Overcurrent:** Analogous to overvoltage, excessive current flowing through the transistor can lead to overheating and failure. Some drivers incorporate protections against this type of failure.
- **Short-circuits:** Automotive motor drives operate in challenging environments, with potential occurrences such as high temperatures, mechanical overloads, short-circuits in motor windings, issues with wiring harnesses, and other critical contingencies like electromagnetic interference or controller malfunctions. These events can result in significant overcurrent levels and even short circuits in the motor drive power circuits, causing device destruction. Many drivers implement current measurement or desaturation detection for overcurrent and short-circuit device protection.
- **Thermal Stress:** Excessive temperature in the transistor can reduce its lifespan and potentially cause semiconductor damage and failure. Overtemperature can result from various factors, including poor soldering, inadequate thermal dissipation systems, overcurrents, manufacturing defects affecting transistor switching, or prolonged operation at excessively high-power levels. Temperature probes near the

transistors or within the modules can be employed to monitor this failure. Some commercial modules already incorporate NTC probes for temperature measurement.

- **Electromagnetic Interference:** Electromagnetic interference can induce false switching in the transistors, leading to short circuits and converter damage. Mitigation measures include designing the converter to minimize parasitic inductance in the power loop and gate-driver circuit, utilizing drivers with differential inputs to prevent noise affecting switching in PWM signals, and employing differential mode transmission of PWM signals or noise-resistant systems such as optical fibre.
- **Mechanical Stress:** Environmental stress factors like vibrations, temperature variations, or humidity can compromise the physical structure of the transistor or cause false electrical contacts. To prevent this failure, the converter should be designed taking into account the expected use conditions and environmental factors. Moreover, additional mechanical sensors could be introduced during the power converter design, such as for instance accelerometers.
- **Sensor Failure:** The various sensors in the converter system are susceptible to failures, typically attributed to ageing. When sensors fail, their readings consistently register as 0. While the failure of temperature sensors is non-critical, as their readings are not utilized in converter control, a malfunction in voltage or current sensors can lead to improper system control operation.

Table 2.2 summarizes the failures detailed above, their causes and their effects.

*Table 2.1: Types of power converter failure, causes and effects.*

| Fault type | Cause | Effect |
|---|---|---|
| Transistor Failure | Overvoltage, overcurrent, false switching, excessive temperature | Transistor destruction |
| DC Bus Breakdown | Overvoltage in capacitors, imbalances in positive and negative semi-buses | Converter destruction |
| Overvoltage | Excessive voltage withstanded by transistors or capacitors | DC bus breakdown. Transistor destruction |
| Overcurrent | Excessive current through transistor | Overheating and failure |
| Short-circuits | High temperatures, mechanical overloads, short-circuits in motor windings, wiring issues, electromagnetic interference, controller malfunctions | Device destruction |
| Thermal Stress | Poor soldering, inadequate thermal dissipation, overcurrents, manufacturing defects | Excessive temperature in transistor, reduced lifespan, semiconductor damage, failure |
| Electromagnetic Interference | Excessive parasitic inductance, crosstalk, bad PCB design | Short circuits, false switching, overvoltage, converter damage. |
| Mechanical Stress | Vibrations, temperature variations, humidity | Compromised physical structure, false electrical contacts |
| Sensor Failure | Aging | Sensor readings consistently register as 0. Improper system control operation |

# 4 TYPES OF FAULTS IN THE eMOTOR

Failures in the electric motor can have various origins, from failures related to extreme operation (frequent overloads, violent transients or harsh environment) that can lead to premature degradation, to electrical failures due to aging due to incorrect design or poor sizing of the components.

The faults that can arise in the eMotor are outlined. The primary failures that may occur include:

- **Stator Faults**: These include short circuits or open circuits in the stator windings, and grounding errors, which can lead to unbalanced currents, reduced torque production, and overheating of motor.
- **Rotor Faults**: Rotor faults can manifest as PMs demagnetization and rotor eccentricities, resulting in torque pulsations, increased vibrations, and reduced motor efficiency. Demagnetization can appear due to high/short-circuited stator current and high rotor temperatures.
- **Sensor Faults**: Sensor faults, such as failures in speed or position sensors, can result in inaccurate measurements, leading to degraded motor control performance.

Therefore, in PM AC motors, faults can appear in the stator or rotor. In the stator, electrical failures may appear in the windings, such as insulation failure, short circuit between winding turns, winding to ground failure and short circuit between phases, while in the rotor the failures affect the magnetic circuit or the mechanical system, such as faults in bearings due to degradation of the lubricating grease or eccentricity of the shaft, due to mechanical stress and deformation.

In a PM motor, electrical failures are mainly related to problems in the stator, and the most frequent is the short circuit between turns of the stator windings. Insulation failure can arise due to normal aging or continuous overheating and overload conditions, producing insulation deterioration and ultimately short circuits between the stator turns. These faults cause rapid propagation, generating faults between phases or between phases and ground.

Mechanical failures are mainly due to bearing breakage. These failures are caused by poor lubrication, shaft misalignment and constant overload. Furthermore, even in normal operation, the bearings suffer great fatigue and are constantly subjected to rigorous working conditions. Common mode current discharges through the bearing cause deterioration of the grease and also cause damage to the bearing. Therefore, bearings are very critical components. Bearing damage can also cause additional types of failures, such as: air gap eccentricity, friction, and electrical failures.

Permanent magnets within the PMSM can experience demagnetization as a result of factors such as high temperature, high stator currents, and the natural aging process of the magnet material. This failure will lead to insufficient torque, generating an increase in current and temperature, which further aggravates demagnetization.

In the case of the electric powertrain, the failures can also come from the sensor. The sensors used for motor control are current sensors and position or speed sensors.

In general, the current sensors used by the control are Hall Effect type. The main faults of the current sensor are gain variation, offset, saturation, sensor noising, and open-circuit and intermittent disconnection of circuit. Position and speed sensors are usually encoders or resolvers. In general, position/speed sensors may have fault conditions because intermittent sensor connection, sensor gain drop and DC bias, and complete sensor failure, Sensor faults lead to a momentary or total lack of information, which lead to instabilities in closed loop control.

Table 2.3 summarizes the failures detailed above, their causes and their effects.

*Table 2.3: Types of PM motor failure, causes and effects.*

| Fault type | Cause | Effect |
|---|---|---|
| Short Circuit (inter-turn) | High temperatures, mechanical overloads, aging, overheating and overloads, wiring issues, electromagnetic interference, controller malfunctions | Peak circulated current, excessive heating, wire insulation damaging. Phase-to-Phase and Phase-to-Ground faults. Demagnetization. |
| Demagnetization | High temperatures, large stator currents, large short-circuit currents produced by inverter or stator faults. Aging of the PM. | Insufficient torque and current increments, which raises the temperature. Abnormal vibration and acoustic noise. Reduced motor performance and efficiency |
| Overvoltage | Excessive Phase-to-Phase voltage due to inverter malfunction | Insulation breakdown. Windings and ground short-circuit |
| Thermal Stress | Excessive load, poor power condition, effective service factor and excessive stops and starts. Environmental influences. | Rapid deterioration of the winding insulation within motors (10°C of additional heat cuts insulation life in a half). |
| Electromagnetic Interference | Excessive parasitic inductance, crosstalk, bad cables shielding | Degraded motor performances, motor damage. |
| Mechanical Stress | Eccentricity. Shat bending, Poor lubrication of the bearings. Temperature variations. | Bearing faults. Torque ripple. Compromised physical structure, friction stator-rotor, false electrical contacts. Windings disconnections. |
| Sensor Failure | Sensor disconnection. Aging (offset/saturation). | Vibrations/stuttering at high currents, commutation errors. Motor destruction. Offset/saturation failures can produce torque ripples and instabilities. |

# 5 AVAILABLE SENSORS AND FUNCTIONS TO IMPLEMENT

To prevent unsafe operations, it is crucial to continually monitor the status of both the converters and the motor throughout their operation. Achieving this task involves the installation of various essential sensors.

The specific sensors required for this purpose are detailed in Table 3.1. However, a more detailed description, with the characteristics of the sensors employed in the project for the low-power, the high-power converter and the motor, is in deliverables D2.1 and D1.4.

*Table 3.1: IMD sensors and their functions.*

| Sensor attached to | Sensor Parameters | Function | Installed on: | |
|---|---|---|---|---|
| | | | Low-Power Converter | High-Power Converter |
| Power Converter | Input voltage of the converter | Measures the DC bus voltage for detecting: overvoltage, short circuits, bus voltage unbalances. | Yes | Yes |
| Power Converter | Output current of phase A,B,C | Measure the converter output phase current for detecting overcurrent. Mechanical failures in the motor, can also, be identified. | Yes | Yes |
| Power Converter | Output voltage of phase A,B,C | Measure the converter output voltage to detect incorrect transistors switching | Yes | No. Variable calculated |
| Power Converter | Temperature of the power converter | Measures the semiconductors temperature to avoid components damage | Yes | Yes |
| Motor | Temperature of the motor | Measures the stator temperature to prevent motor overheating. | - | - |
| Motor | Rotor position | Measures the rotor angle to calculate speed. Likewise, mechanical failure in the motor shaft and bearings can be detected. | - | - |

The functionalities of these sensors are the following:

- The current sensors measure the output phase currents of the converter, permitting the detection of overcurrent produced by an overload condition or short circuit failures. Additionally, enable the shift between the two operation modes of the converter, from two-level to three-level or vice versa. In the same way, the feedback from current phase sensors, is essential for close loop control operation. Finally, by processing the phase current signal, it is possible to identify mechanical problems in the motor, related to bearing faults and rotor misalignment, that may produce distortion in the magnetic flux distribution inside the motor, therefore affecting the stator currents.
- Through the DC bus voltage sensors, the system control can detect if there are short circuits in the semiconductors or failures in the capacitors. Meanwhile, the primary role of the output voltage sensors is to allow the controller to determine if the converter is switching correctly. In the high-power converter, the output phase voltage will be obtained through calculation.
- In order to supervise the correct performance of the converter semiconductors and modules, the insertion of temperature sensors is crucial. These devices detect the temperature of the transistors, (SiC and GaN transistors), preventing abnormal operation and, therefore, semiconductor failures. In addition, the temperature of the motor stator winding will be monitored, enabling the control to derate the output power in the event of overheating. Excessive heat can degrade the insulation of the winding, resulting in electrical faults and short circuits.
- The position of the rotor will be obtained by a resolver sensor, allowing the converter controller to calculate the speed. These signals feedback is necessary for close loop operation of the motor. In the same way, tracking the speed will enable the controller to ensure the motor operation within its nominal speed range. Additionally, mechanical failures could be identified by examining the resolver signal. Variation in signal’s amplitude or phase may suggest a shaft deformation, eccentricity or bearing issues.

The reading from the previous sensors is sent to the power converter CPU so that it closes the control loop and applies the necessary local fault detection algorithms. These sensors are physical connected to the input interface.

Program algorithms process this data to oversee, control, and safeguard the power converter and the motor in real time.

# 6 FAULT DETECTION, IDENTIFICATION AND MITIGATION ALGORITHMS

This section outlines the various detection, identification, and mitigation algorithms intended for implementation in the developed IMD.

As an initial comment, it should be said that the detection of failures in the IMD responds to two different functions:

- on the one hand, immediate **detection of critical situations** in the operation of the drive (for example, desaturation of the WBG switch device that indicates a short circuit). These critical situations, which are identified by exceeding a safety threshold in the measured variable, act immediately at the CPU level of the power inverter.
- on the other hand, **analysis of the evolution of plant signals**, such as temperatures, current harmonics or vibrations, which indicate the appearance of an anomalous situation that can lead to a critical failure in the future.

The first type of signals is associated with drive protection algorithms, while the second is used to establish control or predictive maintenance protocols.

While these algorithms collectively form a unified fault tolerance algorithm, we have categorized distinct parts based on their respective functions. These categories include detection algorithms and localization algorithms.

## 6.1 FAULT DETECTION ALGORITHMS

Fault detection algorithms ascertain the presence of system faults by analysing data from various sensors. Some of these algorithms were initially formulated during WP2, specifically outlined in D2.1. Nonetheless, this document presents a redefined version of these algorithms.

### 6.1.1 POWER CONVERTER

Within the power converter, faults are identified through the examination of temperature sensors, DC bus voltage sensors, and voltage sensors measuring the output voltages. The following subsections describe the proposed simple but robust fault detection algorithms based on measurement thresholds.

#### 6.1.1.1 SEMICONDUCTORS' TEMPERATURES

Temperature sensors play a crucial role in overseeing the temperatures of the semiconductors. Beyond safeguarding the converter, this monitoring facilitates the detection of anomalous temperature levels. Consequently, should one transistor exhibit a substantially higher or lower temperature than its counterparts, it may indicate a potential failure. It is noteworthy that monitoring the temperatures of transistors not only enables detection but also aids in identifying the specific faulty semiconductor.

The essential part of the temperature monitoring algorithm, concerning safety, is the part responsible for detecting overtemperature. This is accomplished by

$$T_{c\_xy} > T_{cmax} \tag{1},$$

where $T_{c\_xy}$ is the case temperature of transistor *y*, where $y = \{1,2,3,4\}$ of phase *x*, and $x = \{a, b, c\}$ and $T_{cmax}$ denotes the maximum allowed case temperature.

Moreover, the temperatures of individual transistors within each phase are monitored to identify any significant discrepancies. SiC and GaN exhibit distinct thermal conductivities, with SiC being an efficient conductor and GaN displaying notably lower thermal conductivity, even inferior to silicon. Consequently, it is necessary to examine SiC and GaN transistors separately.

For SiC transistors within the same phase, their temperatures should ideally align, accounting for an inherent difference between the top and bottom transistors. Analogously, the temperatures of GaN transistors should exhibit a similar pattern. Hence, a substantial variance in temperatures may signify a potential semiconductor failure. The equations explaining this behaviour are

$$\varepsilon > \left|T_{c\_x1} - T_{c\_x4}\right| \text{ for SiC} \tag{2}$$

$$\varepsilon > \left|T_{c\_x2} - T_{c\_x3}\right| \text{ for GaN} \tag{3}$$

where $\varepsilon$ is a certain threshold value.

#### 6.1.1.2 DC BUS VOLTAGES

T-type converters have a split DC bus to connect the central branch to the midpoint of the bus and thus generate the “0” voltage level. Usually, in these converters the upper and lower sub-buses are measured to verify the state of charge of the bus and see if it is balanced. The proposed converter uses three voltage sensors to measure the voltages in the DC bus: one for the upper sub-bus, one for the lower sub-bus and one for the total bus voltage. It must always be fulfilled that:

$$\varepsilon > |V_{DC} - (V_H + V_L)| \tag{4}$$

where $\varepsilon$ is a certain threshold value, $V_{DC}$ is the total bus voltage, $V_H$ is the upper sub-bus voltage, and $V_L$ is the lower sub-bus voltage. Ideally, the threshold should be zero but it may not be due to non-idealities in the measurement, noise and sensor accuracy among other parameters. Therefore, an acceptable threshold value must be determined experimentally. Note that it may be necessary to filter the voltage measurements so that spurious voltages do not trigger the DC bus imbalance alarm.

There is always a delay between a fault and its detection. To minimize this response time alarms are configured for the previous voltage sensors. It is an indicator of fault that a voltage sensor detects a value too high (higher than $V_{DC}$ or $V_{DC}/2$) or too low (close to 0). These faults may be due to a fault in the capacitors or the sensor itself, although normally when a sensor fails its reading is a constant zero (Becker et al., 2021). These faults can also occur in case of a short circuit in the transistor.

#### 6.1.1.3 OUTPUT VOLTAGES

Each phase of the converter can produce three different output voltage values: $V_{dc}/2$, -$V_{dc}/2$ and 0. The output voltage depends on the transistors' state, as shown in Table 5.1.

*Table 4.1: Possible states of the T-type converter.*

| $S_{x1}$ | $S_{x2}$ = not($S_{x4}$) | $S_{x3}$ = not($S_{x1}$) | $S_{x4}$ | $V_x$ |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | --- |
| 0 | 1 | 1 | 0 | 0 |
| 0 | 0 | 1 | 1 | -$V_{DC}/2$ |

| $S_{x1}$ | $S_{x2}$ = not($S_{x4}$) | $S_{x3}$ = not($S_{x1}$) | $S_{x4}$ | $V_x$ |
|---|---|---|---|---|
| 1 | 1 | 0 | 0 | $+V_{DC}/2$ |
| 1 | 0 | 0 | 1 | Not possible |

The switches $S_{x2}$ and $S_{x3}$ always have an opposite state to $S_{x1}$ and $S_{x4}$, respectively. Therefore, we can determine the output voltage of a phase of the converter by simply looking at the state of $S_{x1}$ and $S_{x4}$. The equation that defines the theoretical output voltage of phase *x* of the converter is:

$$V_x^* = S_{x1} \cdot \frac{V_{DC}}{2} - S_{x4} \cdot \frac{V_{DC}}{2} \quad (5),$$

where $S_{xi}$ can take the values 0 when the transistor is open, and 1 when it is closed.

After calculating the theoretical output voltage, it is compared with the actual voltage according to

$$\varepsilon > |V_x^* - V_x| \quad (6)$$

As shown by (3), the error must be lower than a certain threshold, which must be determined experimentally. If the error is higher than that threshold, there is a fault in the converter.

An additional time requirement can be implemented to declare a fault. The output of the previous comparison, i.e.,$\varepsilon$ enters a counter. When this signal is 1, the value of the counter increases. The value of the counter keeps increasing until the output of the comparison is 0, and then it resets. If the value of the counter is higher than another threshold, "*N*", a fault in the converter is declared. Figure 4.1 shows the schematic of the fault detection algorithm for the output voltages. This scheme can be extrapolated for the rest of the faults.

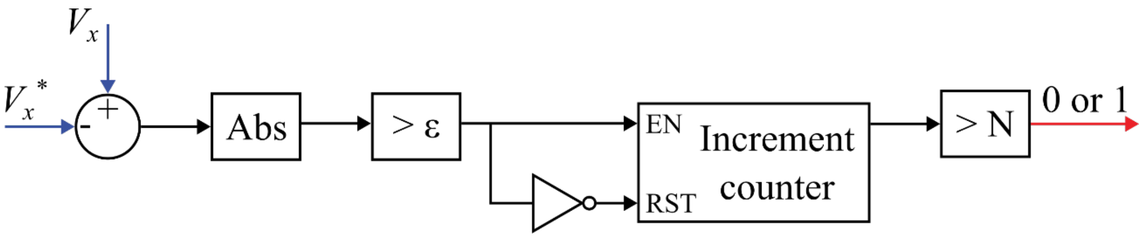


*Figure 4.1 Schematic of the fault detection algorithm for output voltages*

### 6.1.1.4 OUTPUT CURRENTS

The designed power converter is equipped with current sensors to monitor the output currents, i.e. the currents supplied to the electric motor. This monitoring is essential for closing the control loop and ensuring proper motor control. Additionally, the output currents serve as a means to identify potential faults in the power converter. Elevated currents may damage one or more transistors, with overcurrents being detected by

$$|I_x| > I_{max} \quad (7)$$

where $I_x$ represents the output current of phase *x*, where $x = \{a, b, c\}$, and $I_{max}$ denotes the maximum current permissible for the power converter.

It is crucial to note that the maximum current for GaN is lower than that of SiC. Consequently, this reading can be leveraged to modify the operating mode. If the currents surpass a predefined threshold, an instruction is issued to deactivate the GaNs, operating solely with SiC, akin to a two-level converter. Furthermore, when the output current falls below a certain value, an order can be issued to reactivate the GaN transistors, effectively operating as a three-level converter. The equations governing this behaviour are

$$|I_{th} + \varepsilon| > I_{\max\_GaN} \tag{8}$$

$$|I_{th} - \varepsilon| < I_{\max\_GaN} \tag{9}$$

Where $\varepsilon$ is a specific threshold and $I_{max\_GaN}$ is the maximum current allowed at the GaN transistors. The incorporation of this threshold in the equations introduces a degree of hysteresis to the system, preventing continuous oscillation between the two-level and three-level modes.

### 6.1.2 eMOTOR

In order to prevent the electric machine from unwanted behaviour and its eventual breakage, it is necessary to monitor some parameters. The low voltage connector, which interfaces to the inverter, includes the sensors pins necessary to the monitoring. It includes:

- A thermal sensor: which interface parameters detailed in the D1.4,
- A resolver: with its interfaces and specification also detailed in the D1.4.

The list of EM faults to be monitored based on EM sensor acquisition and basic actuations to detect the fault are:

#### 6.1.2.1 ELECTRICAL FAULTS

- EM Temperature sensor fault:

Root level detection: voltage of temperature sensor acquisition. If temperature sensor voltage is below a “min” voltage acquisition or over a “max” voltage acquisition then sensor fault is risen.

- EM Resolver sensor fault:

Root level detection: voltage of resolver sensor acquisition. If the resolver of sensor voltage is below a “min” voltage acquisition or over a “max” voltage acquisition then sensor fault is risen.

#### 6.1.2.2 FUNCTIONAL FAULTS:

- EM Overtemperature:

  Root level detection: EM Temperature sensor. The EM needs to be kept below its maximum temperature to prevent overheating. Fault detection criteria:

  - 0°C < EM T°<160°C Output performance: full performance
  - EM T° > 160°C: NTC offset detection level for safe operation (to be checked on test bench). The functional mode shall be cancelled and inhibited when T° rise NTC offset level to protect the EM.
  - EM T° > 180°C: Overheating (absolute max level getting unreversed EM failure).

- EM Position:

  Root level detection: EM resolver sensor (angular position). The position of the rotor is necessary to be able to control the EM properly. Consequently, its monitoring is essential in order to avoid unwanted behaviour.

- EM Overspeed:

Root level detection: EM resolver sensor (angular speed). EM needs to be kept below its maximum EM operational speed which is 10500 rpm max.

- EM Insulation:

  Root level detection: EM motor phase current leakage to ground. Measure insulation resistance of 400 MOhm min has to be measured before EM start.

Apart from these eMotor fault detection procedures above described, ML algorithms will be developed and applied to electrical and mechanical motor measures, in order to extract motor fault features and perform predictive fault detection. Algorithms are described in Section 6.2.2.

## 6.2 FAULT LOCATION ALGORITHMS

This subsection details different fault location algorithms applicable to the converter and the electric motor. It describes the localization algorithms proposed for the converter, which activate when the algorithms outlined in Section 6.1 issue an error or warning message. Additionally, it explores potential fault detection localization algorithms for the electric motor.

### 6.2.1 FAULT LOCATION ALGORITHMS FOR THE POWER CONVERTER

Detecting faults in a power converter is a complex process. In many cases, a large number of sensors are required to accurately determine which component is failing [1], [2]. One of the objectives of the RHODaS project is to build a power converter as compact as possible so that it is convenient to avoid using many bulky sensors. Additionally, the designed converter must be modular to allow easy replacement, repair and scaling.

This section outlines the localisation algorithms intended for implementation in the low-power converter. Details regarding the algorithms for the high-power converter are currently withheld, as the development of this converter is still in progress. The ultimately implemented algorithms will be elaborated upon in the subsequent release of this deliverable, scheduled for M29. Each module of the low-power converter includes one of the phases of the converter with its respective split DC bus and the corresponding voltage and temperature sensors.

Figure 4.2 illustrates a module of the low-power converter alongside its corresponding sensors. Each module is equipped with three voltage sensors – two for the DC bus halves and the third for the output voltage. Additionally, there are four temperature sensors, allocated individually to each transistor, along with a current sensor dedicated to measuring the output current. The integration of these sensors facilitates the execution of the majority of algorithms expounded upon in Section 4.1.

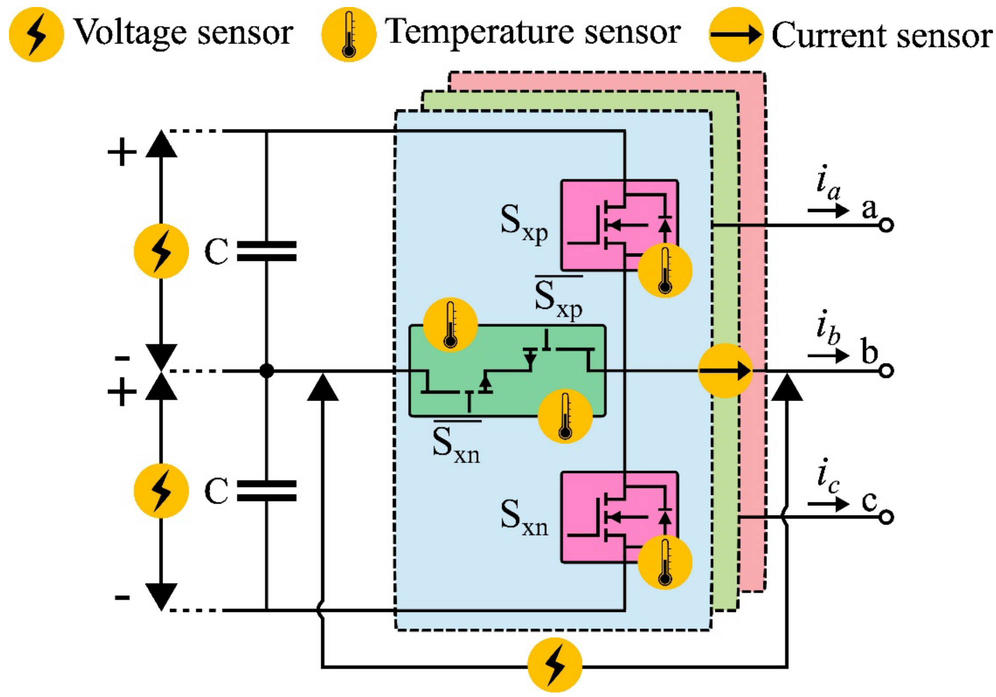


*Figure 4.2 Scheme of a low-power converter module with its respective sensors*

This modular approach presents several advantages related to faults. As previously mentioned, each of the modules incorporates its own sensors. Therefore, it can be easily determined in which module the fault occurs. Once the faulty module has been determined, it can be easily replaced by another one, allowing the normal operation of the converter while repairing the module with the fault. However, fault detection is not limited to the module. Depending on the algorithm that detects the faults, we can know with greater precision what type of fault has occurred or even what specific component has failed.

The temperature algorithm allows us to identify precisely the transistor that presents an anomalous temperature since the temperatures of all the transistors are measured. Thus, if this algorithm detects a fault, it is known exactly which transistor and in which module it has occurred.

The overcurrent algorithm plays a pivotal role in detecting situations where an unusually high current is circulating within one of the converter modules. Thanks to the presence of sensors in each module, this algorithm proves instrumental in discerning precisely which module is experiencing abnormal current flow. Consequently, it becomes a valuable tool for identifying potential faults within the converter system, allowing for targeted troubleshooting. In further detail, the algorithm's functionality lies in its ability to analyze the current readings from individual modules. By comparing these readings against predetermined thresholds, the algorithm can flag modules where the current exceeds acceptable limits. This detailed analysis not only aids in localizing the issue but also contributes to a more comprehensive understanding of the converter's health and performance.

The algorithm of the DC bus voltages indicates if there is a fault in the capacitors of the upper or lower semi-bus. This algorithm does not distinguish whether the fault is from the capacitors or from the voltage sensor. Since the algorithm is applied in each power module, the module and the semi-bus that gives an erroneous reading are located precisely. A risk of this algorithm is that its fault detection depends on the voltage sensor that reads the entire bus voltage. This sensor is located on the motherboard of the low-power converter, so there is a single general sensor for the three modules. If this sensor fails, the algorithm will determine that there is a fault in the three phases of the converter. Therefore, if the sum of the voltages in all the power modules is similar but does not match that of the general sensor of the DC bus, the fault will be in the general sensor.

Finally, there is the output voltage algorithm. This algorithm only compares the desired output voltage with the actual one for each of the phases of the converter. Three-phase converters have the particularity that the phases of the converter work independently. Therefore, if the output voltage does not match the desired one, a fault is declared in the corresponding phase. This algorithm only allows us to discern in which module the error is located but does not determine which transistor is failing. To determine precisely the faulty semiconductor, it is necessary to check the temperature algorithm or to activate the different transistors in a controlled environment, such as a laboratory, and measure precisely the corresponding parameters. Table 4.2 details the key aspects of the detection algorithms discussed above.

*Table 4.2: Proposed fault detection algorithms*

| Detection algorithm | Activation condition | Fault type | Fault area | Localisable fault |
|---|---|---|---|---|
| Temperature | Equation (1) | Transistor failure, thermal stress or overcurrent | Specific transistor | Yes |
| DC bus voltages | Equation (4) | DC bus breakdown, overvoltage, short-circuit or electromagnetic interference | Bus capacitor or voltage sensor | Yes |
| Output voltage | Equation (6) | Transistor failure, overvoltage, short-circuits or electromagnetic interference | Module | Failed module is determined |
| Output current | Equation (7) | Transistor failure or short-circuit | Module | Failed module is determined |

### 6.2.2 FAULT LOCATION ALGORITHMS FOR THE eMOTOR

Signal-based methodologies are principally employed for the processing and extraction of diverse features from motor signals. Signal processing stands as a commonly utilized strategy for fault detection, facilitating the identification and extraction of fault characteristics from signals, notably encompassing current and vibration.

The traditional technique for frequency domain analysis entails the application of fast Fourier transform (FFT). This methodology effectively extracts the frequency distribution of the signal, facilitating the utilization of harmonic components' amplitudes and frequencies as features for various fault types. Stator Motor Current Signature Analysis (MCSA) has begun to provide a more effective and efficient motor fault detection technique based on current harmonic decomposition by Fourier transform or other time-frequency techniques, such as short-time Fourier Transform or Wavelet Transform.

In an electric motor, intrinsic vibrations appear in a natural way due to constructive aspects (number of slots, number of motor poles, etc.), but they can increase in case of coming faults due to mechanical eccentricity, bearings and mechanical coupling damages. Vibration measurements in time domain and also in frequency domain can be done at any time. Frequency components and their amplitudes can be determined and compared with previous measurements, detecting the vibrations changes and trends, and thus forecasting the healthy or faulty state of the powertrain.

The main algorithms to detect and identify these faults are described below.

**1. MCSA methods**

- Electric faults

Imbalances in the stator current and alterations in its amplitude due to electrical faults (short circuits between turns, open phases...) lead not only to changes in current amplitudes, but also to characteristic frequency profiles, in which that the harmonics at specific frequencies reflect the particular fault. For example, in a PM motor, a short circuit in the winding causes a significant amplification of the third harmonic amplitude.

- Mechanical Faults detection.

Mechanical faults and mechanical unbalances create irregularities in the flux distribution within the motor, consequently causing stator current harmonics. As in the case of stator electric faults, these harmonics' frequencies also reflect the type of fault, either eccentric faults or bearing faults. Fault frequencies have previously been determined and are available from the specialized literature.

- Demagnetization fault:

In the case of demagnetization fault the resulting distributed magnetomotive force (MMF) deviates from a sinusoidal pattern. Both the functional and faulty segments of the MMF contribute to generating a current with multiple frequencies. Consequently, when demagnetization occurs, low-frequency components manifest near the fundamental wave within the current signal. For example, the harmonics 0.25th, 0.5th and 0.75th are ideal indicators to separate a demagnetization fault from the static eccentricity fault

**2. Vibration analysis**

Vibration signals become extensively used nowadays as effective parameters for feature extraction and health monitoring of eMotor drive. These signals can be measured using various sensors, such as accelerometers or displacement transducers. Vibration analysis can be performed in both time and frequency domains.

In **time domain vibration analysis**, vibrations are recorded as temporal signals, which represent the amplitude of the vibration as a function of time. In this way, it is possible to analyze the changes or vibration patterns using different parameters or metrics, such as the peak, peak-to-peak and RMS values (which represents the vibration energy) of the acquired signal.

**Frequency domain measurement** is another critical vibration measurement technique. Time domain signals are transformed into frequency domain signals using mathematical tools such as Fast Fourier Transform (FFT) or wavelet transform. This process helps isolate and analyze individual frequency components of the vibration signal, which are directly related to specific faults such as rotor eccentricity and bearing damage. Furthermore, power spectrum density (PSD) can be obtained from harmonic decomposition, which provides an accurate measure for comparing random vibration signals that have different signal lengths.

## 6.3 FAULT TOLERANCE ALGORITHMS

Fault-tolerant control techniques relies on fault detection followed by fault reconfiguration. Various fault detection techniques included in RHODaS are as follows:

- Model-Based Methods: These methods involve using mathematical models of the motor and comparing the model predictions with the measured/stablished (thresholds) values on the model to identify discrepancies caused by faults. This method is used in RHODas for failure protection at the Inverter CPU level.
- Signal Processing Techniques: Signal processing techniques, such as Fourier analysis, wavelet analysis, or envelope analysis, can be used to analyze power train signals and extract fault-related information. Signal processing is executed in RHODaS in the intermediate Gateway/ECU of the vehicle.
- Data-Driven Methods: Data-driven approaches employ machine learning algorithms to analyze historical motor data and identify patterns indicative of faults. A pattern recognition method using AI and ML (such as for instance Support Vector Machine, SVM, or Artificial Neural Network, ANN) could be used in next steps, once an abnormal operation is detected, to identify types as well as severities of existing faults. This kind of algorithms are proposed to be used in the edge (Gateway) or on the cloud, to stablish Predictive Maintenance algorithms, to estimate Remaining Useful Life, etc.

Additionally, redundant sensors can be employed to cross-check measurements and detect inconsistencies or discrepancies that may indicate faults.

In the RHODaS approach, the proposed fault tolerance algorithm will run on the ECU, although in the prototype it can be implemented by sharing algorithms on the Gateway and Cloud CPUs. The firmware embedded in the processors of the IMD diligently monitors dedicated hardware fault signals and analog inputs encompassing various currents, voltages, and temperatures. In the absence of any detected faults, the control seamlessly transitions to the machine control algorithm. However, should an error be identified, its severity undergoes algorithmic classification into either a soft or hard error condition. Notice that the ECU can also receive fault signals from the gateway.

In the event of a hard error, indicating an imminent risk of hardware damage, an immediate shutdown is initiated, precluding the invocation of the control algorithm. Conversely, when a soft error is detected, the hand-off to the machine control algorithm still occurs, but a predefined shutdown procedure, if implemented, is activated. The control algorithm retains the capability to initiate a controlled shutdown independently.

Beyond soft and hard errors, the system also accommodates the issuance of warnings. Warnings primarily serve an informative purpose for both the control algorithm and the user through the Human-Machine Interface (HMI). It is anticipated that the control algorithm autonomously manages warnings. For instance, the responsibility of power derating upon a temperature warning lies within the domain of the control algorithm. If the algorithm fails to prevent an over-temperature scenario, a soft or hard error, contingent on the configuration, is triggered.

The aforementioned processes can be visually represented in a figure to enhance comprehension. Figure 4.3 illustrates the proposed fault tolerance algorithm in a flowchart.

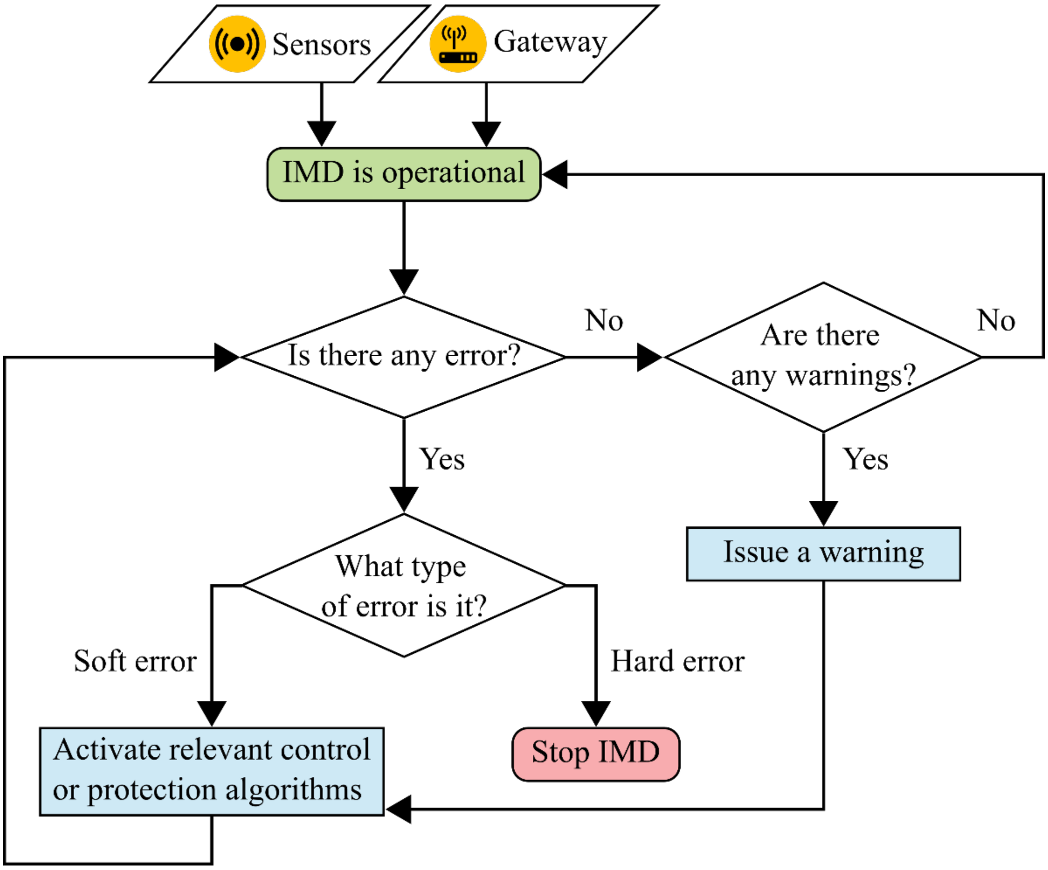


*Figure 4.3 Flowchart of the proposed fault tolerance algorithm*

A critical aspect of the previous flowchart are the control and/or protection algorithms. While these algorithms necessitate further detailed definition and study, their primary objective is to enable the continued operation of the power converter, and consequently, the IMD, in the face of a soft error and/or a warning. Currently, two proposed algorithms are under consideration:

- **Derating Algorithm:** This algorithm is designed to decrease the output power of the converter. Reducing the power output proves advantageous and crucial in specific scenarios. Firstly, it plays a pivotal role in safeguarding the IMD by effectively mitigating overload situations. Furthermore, the reduction in the converter's output current contributes to temperature control, preventing overheating within the system. Lastly, in instances where the converter operates in a 3-level configuration, the adjustment in output current significantly influences the currents flowing through the DC bus. By reducing these currents and, consequently, the power, a balanced distribution on the DC bus is kept. This balance is essential for the seamless operation of the converter, ensuring optimal performance.
- **Two-Level Operating Algorithm:** As mentioned earlier, the power converter operates in two modes – one as 2-level and the other as 3-level. During the two-level working mode, only SiC transistors are switching. This mode can be activated if a potential failure in the GaN transistors is detected. Furthermore, 2-level converters inherently maintain a balance between the two DC semi-buses. Consequently, this operating mode can also be engaged in the presence of significant imbalances on the DC bus. Figure 4.4 shows the operation modes of the power converter.

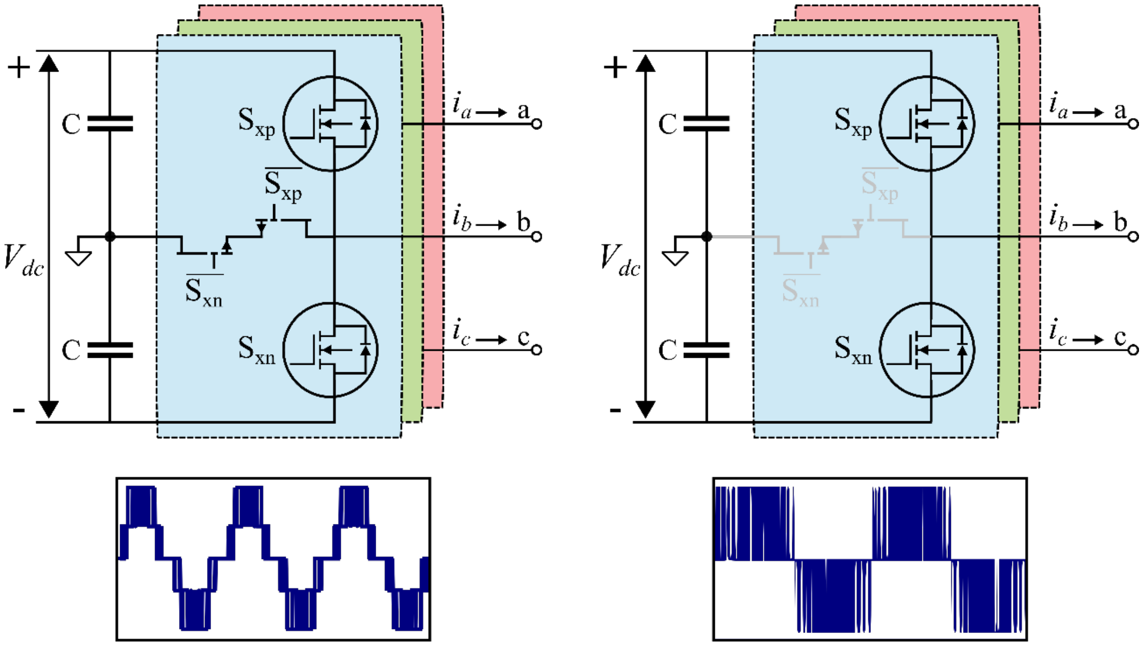


*Figure 4.4 Proposed operation modes.*

Table 4.3 summarizes the proposed mitigation algorithms, established clear connections with their respective detection algorithms and the specific types of failures they address. An important consideration is that the choice of which mitigation algorithm to apply hinges on the precise location of the identified failure within the system. Two-level operation algorithm is specifically designed to address failures in the GaN transistors or imbalances detected within the DC bus. Its effectiveness is tailored to these particular situations, providing targeted responses to ensure system stability and reliability. Conversely, the derating algorithm offers a more versatile approach, capable of addressing a broader spectrum of situations. This algorithm comes into action in instances that go beyond the specific scenarios covered by the two-level operation algorithm. Its adaptability allows it to respond to various conditions, contributing to system resilience and overall performance optimization.

*Table 4.3: Proposed fault mitigation algorithms*

| **Detection algorithm** | **Fault type** | **Mitigation algorithm** |
|---|---|---|
| Temperature | Transistor failure, thermal stress or overcurrent | Derating & Two-level operation |
| DC bus voltages | DC bus breakdown, overvoltage, short-circuit or electromagnetic interference | Two-level operation |
| Output voltage | Transistor failure, overvoltage, short-circuits or electromagnetic inferference | Derating & Two-level operation |
| Output current | Transistor failure or short-circuit | Derating & Two-level operation |

# 7 CONCLUSION

This deliverable focuses on fault-tolerant control strategies for SiC/GaN power converters. The key outcomes of this deliverable are briefly summarized as follows:

- **Fault-Tolerant Control:** This deliverable defines the concept of fault-tolerant control and describes the control levels within the proposed IMD. The power converter control system swiftly addresses faster and more critical faults, while the Gateway performs the pre-processing of the data and extracts fault features, managing faults at featuring slower dynamics. Finally, the cloud manages faults demanding extensive data processing and a high computational burden.
- **Types of Faults in the Converter:** The deliverable details the potential faults that could manifest within the power converter. Moreover, it also explains strategies for fault detection, where feasible.
- **Types of Motor Faults:** Similar to the converter faults, this deliverable comprehensively outlines potential faults that may manifest in the electric motor.
- **Sensors and Functionalities** A detailed examination is conducted on the array of sensors integrated into the power converters, elucidating the functions that will be implemented based on the data collected. Additionally, the deliverable expounds upon the sensor reading architecture, specifying the flow of information from sensors to the power converter and subsequently to the Gateway and the IoT platform.
- **Detection and Localization Algorithms:** The deliverable presents the proposed algorithms designed for the detection and localization of faults. It presents the equations governing these fault detection algorithms, explaining their operational mechanisms. Detection algorithms are explained and related to preceding localization algorithms, specifying their precision in determining the fault location or if they are limited to a specific area, such as one of the converter modules.
- **Fault Tolerance Algorithms:** The document meticulously elaborates on fault tolerance algorithms applicable to the system. Specifically, for the power converter, it presents two implemented algorithms. Firstly, a derating algorithm is described, strategically reducing the converter's output power. Additionally, it outlines an operating mode change algorithm activated in the event of GaN transistor failures or imbalances in the DC bus.

Table 5.1 sums the deliverable's contents. The table categorizes the types of faults that may occur in the converter, clarifying whether they are directly detected by the proposed algorithms, if they can be precisely located, and, when applicable, and the specific area within which the algorithm would identify the fault. Additionally, the table meticulously outlines the indispensable sensors required for enabling fault detection and localization. Finally, the table indicates whether the fault tolerance algorithms proposed in this deliverable can effectively mitigate the described types of failures.

*Table 5.1: Potential converter failures and corresponding sensors and algorithms for detection and localization*

| Fault type | Detected | Sensor location | Related sensor | Mitigated |
|---|---|---|---|---|
| Transistor Failure | Not directly | Not applicable | All sensors | Yes |

| Fault type | Detected | Sensor location | Related sensor | Mitigated |
|---|---|---|---|---|
| DC Bus Breakdown | Not directly | Module | Voltage sensors (DC bus) | Yes |
| Overvoltage | Yes | Module | Voltage sensors | Yes |
| Overcurrent | Yes | Module | Current sensors | Yes |
| Short-circuits (inverter and motor) | Not directly | Not applicable | Voltage and current sensors. Accelerometers | Yes |
| Thermal Stress (inverter and motor) | Yes | Not applicable | Temperature sensors | Yes |
| Electromagnetic Interference | Not directly | Not applicable | Voltage sensors | No |
| IMD mechanical stress | No | No | Accelerometers | No |
| Sensor Failure | Yes | Yes | All sensors | No |

The report provides a comprehensive understanding of fault-tolerant control mechanisms, setting the stage for further advancements in the RHODaS project.

There are no deviations in the current deliverable, preventing the need for contingency measures at this stage.

## REFERENCES

[1] F. Becker, E. Jamshidpour, P. Poure, and S. Saadate, ‘Fault detection and localization for T-Type Converter’, in *21st IEEE International Conference on Environment and Electrical Engineering and 2021 5th IEEE Industrial and Commercial Power System Europe, EEEIC / I and CPS Europe 2021 - Proceedings*, Institute of Electrical and Electronics Engineers Inc., 2021. doi: 10.1109/EEEIC/ICPSEurope51590.2021.9584808.

[2] R. Picas, J. Zaragoza, J. Pou, and S. Ceballos, ‘Reliable Modular Multilevel Converter Fault Detection with Redundant Voltage Sensor’, *IEEE Trans Power Electron*, vol. 32, no. 1, pp. 39–51, Jan. 2017, doi: 10.1109/TPEL.2016.2526684.