Protection System Architecture for All-Electric Aircraft

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***Abstract*—To reduce emissions from the aviation industry and meet the targets set by different countries, research has been focused on investigating all-electric aircraft. To make this vision practical, superconducting machines are expected to power the propellers, as they are half the size and a third the weight of conventional machines. The main purpose of this paper is to do a higher-level study of a reliable holistic protection system for all-electric aircraft; that can reduce heat leakage and be able to detect faults reliably. Thus, three main protection systems were investigated; 1) cryogenic voltage source converter superconducting magnetic energy storage system (VSC-SMES), 2) cryogenic dc breaker integrated with superconducting fault current limiter (SFCL), and 3) machine learning algorithm for fault detection. By immersing the protection system at cryogenic temperature, the paper has shown that passive leakage can be eliminated, and thus more energy can be saved for the fuel cell. The paper has also demonstrated that using machine learning for the SFCL-dc-breaker system can consistently eliminate faults and protect the system.**

***Index Terms*— Cryogenic, Discrete wavelet transform, Hybrid dc breaker, IGBT, Machine learning, protection, SMES, SFCL, SVM.**

I. INTRODUCTION

ELECTRIC propulsion has been a major research topic as it promises to slash emissions and meet the stringent policy of countries to reduce fossil fuel and noise from aircraft [1]- [5]. Hydrogen or lithium-ion batteries can provide the energy source for propulsion, whereas [4] has shown that batteries are mainly feasible for short-haul flights for several up to 39 passengers. For long-haul aircraft that can carry a larger number of passengers, hydrogen fuel is a more practical solution as it has a higher power density than batteries [5]. To make all-electric aircraft more practical, superconducting machines are the main focus, as they can take half the size and a third of the weight of copper machines. Hydrogen will then act as both a coolant and fuel for the aircraft.

The architecture of all-electric aircraft is presented in Fig. 1 and based on previous literature [5]-[7], where the entire system is immersed inside the cryostat. From the figure, both the converter and protection systems are immersed inside the cold temperature, this is better from the engineering point of view to avoid complex transitions from cold to ambient temperatures and vice versa, thus reducing heat leakage. Fig.1 shows the protection system in detail, where a dc-breaker is to be used with a superconducting fault current limiter (SFCL) and a superconducting magnetic energy storage system (SMES) in parallel. Using power semiconductors for protection systems at cryogenic temperatures has advantages, as the literature [8],[9] has shown that power electronic devices' performance improves at cryogenic temperatures as their 1) conduction losses and 2) switching decrease. The literature has also shown that semiconductor devices have higher power density at lower temperatures and can improve system efficiency.

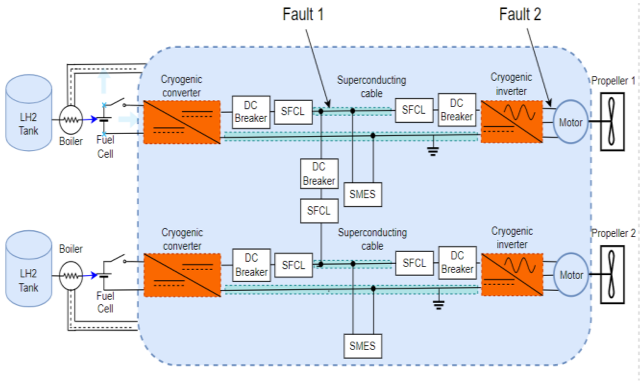

Fig. 1. Architecture of all-electric aircraft

Given that all-electric aircraft require substantial amounts of power, ranging in the multiple MWs, and that the aircraft's operation is heavily dependent on a robust electrical system, it is imperative to develop a protection system that can effectively isolate faults while preserving the network's functionality. This paper focuses on presenting a holistic protection system for all-electric aircraft, where the paper mainly focuses on three protection system requirements; 1) quick fault isolation using dc breakers to protect superconducting cables from getting permanently damaged, 2) maximum duration of the SMES as a backup supply in case of the main supply failure, and 3) effective and accurate identification of short circuit using a machine learning algorithm. For fault isolation, the paper implements

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SFCL that can effectively limit the fault current and avoid system failure. A SMES that uses semiconductor switches at cryogenic temperature will also be studied. A powerful machine learning technique has been developed to identify airplane system faults. This algorithm employs advanced algorithms to scan the system and detect problems at two critical places, as shown in Fig.1. The system is able to learn patterns and discover abnormalities that might suggest possible flaws by harnessing massive volumes of data and employing cutting-edge methodologies. This approach not only guarantees the accuracy of the fault detection procedure but also minimizes the risk of false alerts, leading to a reduction in unnecessary trips. With this formidable tool, the aviation industry is able to identify faults in their aircraft proactively, ensuring the maintenance of a high standard of safety and dependability for both passengers and crew members. The novelty of this paper can be summarized as follows; a) investigating the heat leakage of cryogenic SMES and cryogenic hybrid circuit breaker, b) determining the energy saving of using cryogenic SMES, and c) building a machine learning algorithm with an SFCL in the circuit that can detect a fault and distinguish between faults and overloading conditions.

The paper is divided into the following sections; section II describes the background and offers a brief literature review on cryogenic power electronics, dc circuit breakers, SFCL, and SMES coils. Section III describes the machine learning algorithm that is going to be used to detect faults and trip the necessary protection devices. Section IV shall describe the system design and build a simulation to study the process of loss of supply and the system's performance in case of a fault. Section V shall give the conclusion of the paper.

II. BACKGROUND

A. Review on cryogenic power electronics

Table I shows the performance of semiconductor devices at cryogenic temperatures. The conduction losses can be determined by the on-resistance ($R_{DS(on)}$) for MOSFETs [7]-[14] or the forward voltage ($V_{Forward}$) for IGBT [15]-[17], both of these values decrease for both Si MOSFET and Si IGBT devices and hence are better options to be used at cryogenic temperature. The switching energy (E_{SW}) has been shown to decrease with the decrease of temperature for Si MOSFET and Si IGBT. However, the breakdown voltage ($V_{Breakdown}$) has shown also to decrease for all three devices, thus a safety margin should be added into consideration when selecting the device. To summarize, Si MOSFET and Si IGBT are more suitable for use at cryogenic temperatures.

TABLE I
PERFORMANCE OF SEMICONDUCTOR DEVICES AT LOWER TEMPERATURES

Device type	Parameter	Trend as the temperature is reduced to 77 K
Si MOSFET [7]-[9]	$R_{DS(on)}$	-80%
	$V_{Breakdown}$	-30%
	E_{SW}	-90%
SiC MOSFET [7]-[14]	$R_{DS(on)}$	+300%
	$V_{Breakdown}$	-20%
	E_{SW}	Sparse data
Si IGBT [15]-[17]	$V_{forward}$	-22%
	$V_{Breakdown}$	-30%
	E_{SW}	-70%

B. DC circuit breakers

In [18] a superconducting machine underwent a short circuit fault and was quenched with permanent damage in less than 20 ms, thus a fast and reliable protection system must be in place to limit the short circuit and quickly eliminate the fault. Commercial mechanical dc circuit molded case circuit breakers (MCCB) can have a rating of up to 1000 V and can conduct current up to 5000 A during normal operation and during faults they have a current breaking capacity of up to 70 kA. However, these devices are typically slow as they rely on mechanical operation, and their breaking time can be in the range of 60 ms can lead to permanent damage to the system as discussed earlier [19]-[21]. Thus, a faster protection system is required. Hybrid dc-breakers on the other hand, have a shorter breaking time of 1-2 ms [21]-[25]. Table II shows a comparison between different circuit breaker topologies. From the table, it can be deduced that a hybrid dc breaker is the best solution for fault protection, especially when an SFCL is used in series, as it can effectively limit the fault current.

The hybrid dc-breaker is presented in Fig. 2. As seen it is a combination of an ultrafast switch (UFS) with solid-state devices in parallel to ensure a shorter breaking time. During normal operation, the current is conducted through the UFS as it has lower losses. When a fault occurs, the solid state is energized this provides an alternative path for the current to flow as we try to open the mechanical switch at no current quickly as

TABLE II
COMPARISON OF DIFFERENT DC CIRCUIT BREAKER TOPOLOGIES

Configuration	Topology	Performance
Two branches	Passive resonance [21]	- Slower breaking time= 12ms. - Easy configuration
	Current injection [21]	- Fast breaking time= 5ms. - Complex configuration
	Solid state [21]	- Fast breaking time= 5ms. - Very high voltage across the device during breaking
Three branches	Hybrid breaker [21]	- Fast breaking time= 5ms. - Lower voltage on semiconductor devices.
	Current Commutation hybrid breaker [21]	- Fast breaking time= 5ms. - Capacitor aids limiting of fault. - Eliminates need of semiconductor in the main path.
	SFCL hybrid breaker [21] ,[22]	- Fast breaking time= 5ms. - SFCL helps to limit the fault and eases the breaking of the circuit.

there is no arc. After the safe opening of the UFS, the main breaker is switched off breaking the short circuit [21]. Some research is still needed to investigate how the ultrafast switch in the hybrid dc breaker can be used at cryogenic temperature.

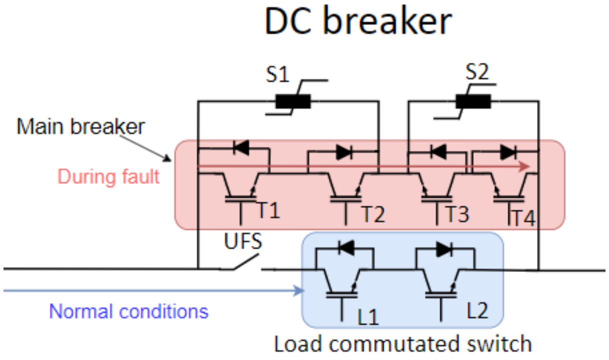


Fig. 2. Construction of hybrid DC breaker

C. SFCL

Superconducting devices are known for their ability to ensure high reliability and continuous load supply. They can provide fault protection by limiting the fault current and providing an alternative source of supply in case of a short loss [26]. Different techniques for fault current limitation use a superconductor, such as resistive or magnetic fault current limiters [26]. As weight and volume are major concerns in an aircraft's system, resistive type superconducting fault current limiter (RSFCL) is used in this study. The RSFCL is a simple and self-healing device with low operational losses. It can limit the fault within a few milliseconds to the desired level in coordination with the circuit breakers. The RSFCL has been used in DC and AC aircraft systems in [27] and [28], respectively.

D. SMES

In case of a disturbance at the generator side, the energy storage device is required to support the critical loads with the required power. SMES has the advantages of high power density, fast response time, and efficient charge and discharge cycles. It has many applications in electric power systems [29]. There are different SMES modules for different power systems; however, a voltage sources converter integrated with SMES (VSC-SMES) is the most suitable for a DC network. In [30], a VSC SMES is used to support the load during voltage dip at the aircraft generator and maintain the propulsion system speed at the required level despite the disturbance at the generator side.

E. Superconducting machines

In [31], different superconducting machines were reviewed, including synchronous, induction, and dc machines. However, literature that utilized models from the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) [32]-[34] has highlighted that a synchronous machine will be easier to cool down than an induction machine. Based on this, the machine model used in this paper is a fully superconducting synchronous machine.

III. MACHINE LEARNING ALGORITHM

For fault detection, several papers have proposed the use of different machine learning algorithms for protection schemes for dc systems. In [35], artificial neural networks (ANN) and support vector machines (SVM) were used to discriminate between internal and external faults. In [36], K-nearest neighbors and SVM were used to identify high-resistance grounding faults. Paper [37] investigated fault probability estimation based on an SVM model. While authors in [38] discuss the application of a fast frequency response control using an HVDC system for a large power system disturbance based on the multivariate random forest regression (MRFR). In [39], a Naïve Bayes classifier was used to identify both the threshold levels and operational time frames for the multi-terminal voltage source converter-based HVDC protection system.

Figure 3 shows the flowchart for training the machine learning SVM model. The figure shows that after simulating a fault on MATLAB/SIMULINK, the output waveform undergoes preprocessing through discrete wavelet transform (DWT). Afterward, this data is fed through a machine learning SVM model to learn from it. After the training phase is implemented, the model is deployed in real-time protection to effectively trip the circuit breaker during the fault.

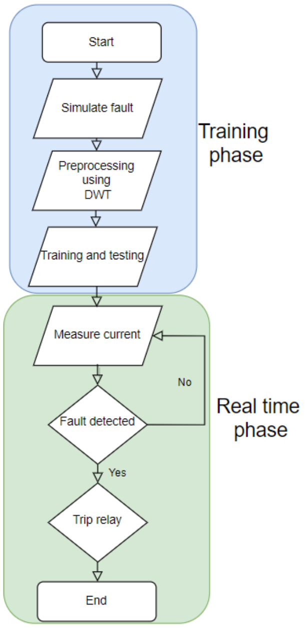


Fig. 3. Flowchart of training SVM model

The application of DWT for fault analysis has been previously explained in [40] and [41]. As illustrated in Fig. 4, a four-level Discrete Wavelet Transform (DWT) has been applied to analyze faults in the system. The DWT process involves applying both a high-pass filter and a low-pass filter to the input waveform at each level. The output of the low-pass filter is stored as (A), while the output of the high-pass filter is stored as (D). The (A) signal from each level is then subjected to the same process four times, eventually resulting in the output signal (A4). This repeated application of high-pass and low-pass filtering helps to decompose the input waveform into its constituent frequencies, providing a more detailed analysis of faults in the system.

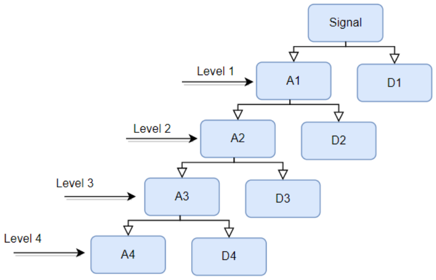


Fig. 4. Discrete wavelet transforms decomposition tree

Figure 5 presents the results from each stage of the filtering process. As the signal is filtered through each level, represented by A1, A2, A3, and A4, it becomes increasingly easy to identify a fault in the network. It is clear from the figure that the output from stage A4 provides a clearer indication of a short-circuit event than the original input signal, allowing the machine learning algorithm to identify this type of fault. This improved distinguishability of the signal at the final stage of filtering makes it easier for the algorithm to identify faults in the network, enhancing the overall performance of the system.

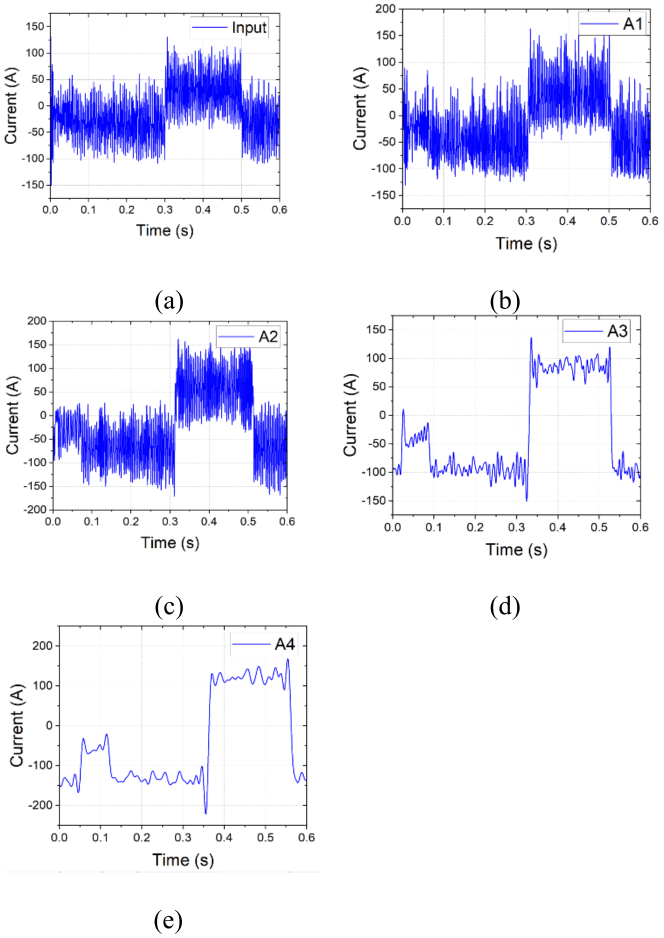


Fig. 5. Filtering output through the DWT at each level; a) Input signal, b) A1, c) A2, d) A3, e) A4

A supervised machine learning technique using SVM was built. SVM has been widely used in regression estimation, pattern recognition, fault diagnosis, system identification, and so on [35]-[37]. SVM mainly uses a hyperplane to classify the data into two different classes by using intuitive geometric meaning as seen in Fig. 6. The main advantages of SVM are; 1) less likely to over-fit, 2) its outstanding feature extraction, and 3) its strong ability to deal with arbitrary data [35]. Although SVM can be used for binary and multi-class classification problems, this paper mainly focuses on the former binary classification. For the SVM parameter, a grid search and four-fold cross-validation are combined. The paper applies the machine learning algorithm SVM as the previous paper, however, the main difference is the novelty of the application of utilizing it for cryogenic SFCL. Training data is fed to SVM so the hyperplane is set to determine which values of current should trigger the circuit breaker and which values of current are normal operating conditions.

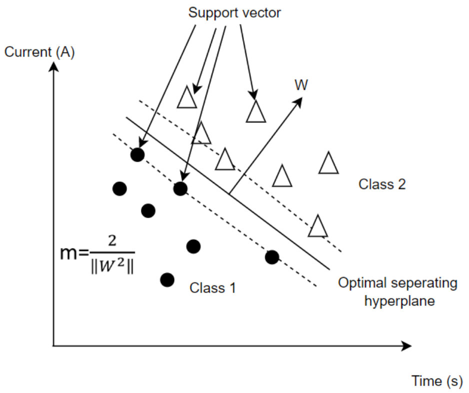


Fig.6. SVM hyperplane classification technique

IV. SIMULATION RESULTS

A. System configuration

The simulated system is shown in Fig. 1, with the rating of each device presented in Table III. The hydrogen fuel cell in the simulation with a voltage rating of 1000V and a rated capacity of 5000AH. The simulated superconducting machine is fully superconducting with a 100kW rating with Sunam SAN04150 tape as in [18]. A resistive type SFCL tape was used, utilizing AMSC type 8612, based on the work done in [42].

TABLE III
SYSTEM PARAMETERS

Equipment	Type	Rating
Supply voltage	Fuel cell	1000 V
Propeller	Synchronous motor	2x100 kW
SFCL	Resistive type	1.2Ω
SMES	VSC based	1 H, 0.5 MJ
IGBT (SMES/ breaker)	Module FZ800R45KL3B5NOSA2	4500V, 1700A

The SFCL was modeled as a non-linear resistance where upon reaching the critical current when the tape quenches, the resistance changes value from the superconducting value $2.85e^{-4}\Omega$ to 0.92Ω this is presented in Fig. 7. For the breaker an IGBT module was used where the parameters at room temperature are taken from the datasheet of the FZ800R45KL3B5NOSA2. For cryogenic temperature, the parameters of the IGBT were modified according to the data extrapolation in section 2. The SMES module is modeled as an inductor of 1 H. For the cryogenic temperature parameters, the model parameters are updated based on the extrapolation done in Table I. The simulated protection system is presented in Fig. 7, where from the figure, an SFCL is integrated with a cryogenic dc breaker to prevent large short circuit currents and offer fast protection. During normal operation, the UFS is connected. Once a fault occurs the UFS is disconnected and the current passes through the parallel branch with the semiconductors, which fully breaks the circuit later. The figure presents a cryogenic VSC-SMES, which is used in case the voltage input sags or surges.

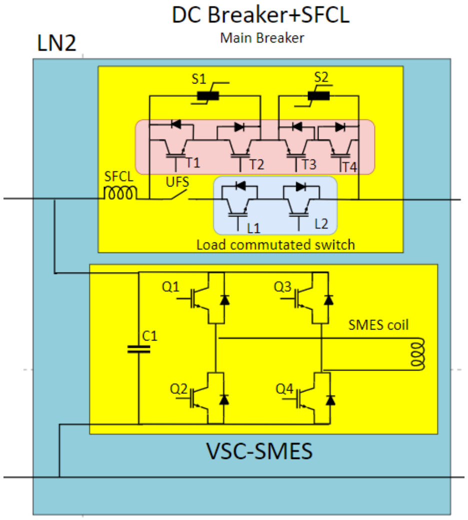


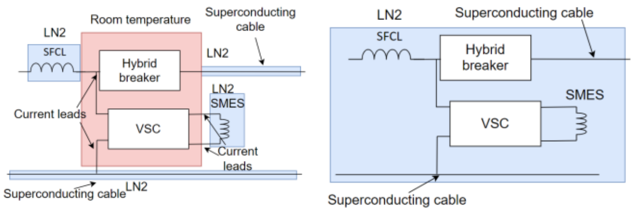
Fig. 7. Protection system for the Hydrogen aircraft

B. Passive heat leakage analysis for hybrid dc breaker and VSC SMES

Immersing both the hybrid breaker and VSC SMES at cryogenic temperature saves passive heat leakage as no copper bars are needed to be extended outside of the cryostat as seen in Fig. 8. The joint resistance between the copper and the superconducting cable can be neglected if good contact surface area is done between both [43]. Equation (1) can be used to calculate the passive heat dissipation if the protection system was at room temperature with current leads extended from the cryostat shown in Fig. 6. Where C_p is the specific heat capacity is 400 w/m/K, A_{busbar} is the area of the copper bar, ΔT is the temperature difference between the room and the setup cryogenic temperature, and L is the length of the conductor.

$$H = \frac{C_p \times A_{busbar} \times \Delta T}{L} \qquad (1)$$

For a 50 mm length bus bar with a surface area of 80 mm^2 and a $\Delta T = 200$ °C, the heat leakage calculations would be 133.3 Watts/second for each copper bar connected. As there are four circuit breakers, each with four bars (input and output), and the VSC SMES requires two, a total of 18 copper bars are required for this setup. Thus, a total of 2.4 kW will be leaked from the system based on equation (1) when the protection system is at room temperature. By immersing the protection system at cryogenic temperature, the heat leakage would be zero as there are no copper bars needed to be extended outside of the cryostat. Meaning that a cryogenic protection system can save 2.4 kW out of the 200 kW system, a saving of 1.2%.



(a) (b)

Fig. 8. Room temperature protection system (a) vs cryogenic protection system (b)

C. Simulation of cryogenic VSC SMES

A simulation was carried out to quantify the saving of using VSC shown in Fig.7 in the highlighted red box at cryogenic temperature, this is done by measuring the duration that the SMES coil is able to power the superconducting motor in case of a loss of supply. In the simulation built, the speed of the motor was set at 1500 rpm and the supply failure was set at 0.3 seconds as seen in Fig. 9. In response, SMES coil was used (Q1 and Q4 switched on) as soon as a loss of motor speed was detected. The simulation was run twice, once when the VSC is placed at room temperature and once when the VSC is placed at cryogenic temperature. Where the difference between both VSC is the reduced forward voltage (-22%) and switching time (-70%) of the IGBT at cryogenic temperature highlighted in the earlier section. The figure shows the drop from the motor speed

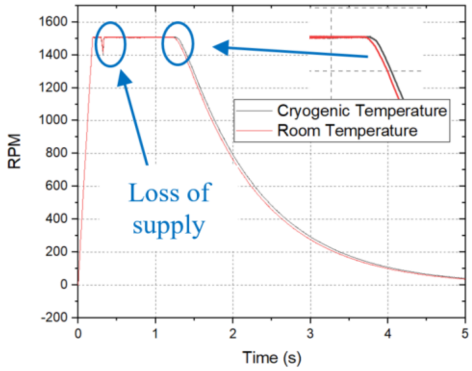


Fig. 9. VSC SMES operating in case of loss of supply at room and cryogenic temperatures

set point for each condition, at 1.255 seconds at room temperature and 1.286 seconds at cryogenic temperature. Thus, saving overall 2%.

D. Simulation of Hybrid DC breaker and detection faults using machine learning algorithms

This section presents a novel study of detecting faults using machine learning algorithms with an SFCL in the circuit. The simulation is conducted as follows; 1) training phase and 2) testing the precision of the machine learning algorithm to detect faults. Two main faults were tested in the system, as seen in Fig. 1 at fault locations 1 and 2. For the first step of the training phase, 100 different faults were fed to the training of the SVM algorithm, with the fault resistance ranging between 1 $m\Omega$ to 20Ω. For each fault, the current and the voltage were sampled for 30 cycles at a sampling frequency of 10 kHz. The data of the 100 faults were then passed on to the DWT for preprocessing and then fed to a Python code using Scikit-learn, finalizing the training. For the second step different faults were emulated to verify the algorithm with table IV showing the results. The precision of the fault prediction is presented in the final column. The results reveal that the SVM algorithms were able to discriminate between faults and normal operating conditions with SFCL in the circuit to limit the fault currents.

TABLE IV
SIMULATION RESULTS

Equipment	Type	Precision
Fault 1	Pole-ground	0.95
Fault 2	L-G	0.96
	L-L	0.95
	L-L-L	0.97

V. CONCLUSION

In this paper, the protection system for all-electric aircraft has been studied, including three main parts, 1) fault limiting and isolation, 2) loss of supply, and 3) fault detection. The system analysis has shown that immersing the hybrid circuit breaker, SFCL, and VSC SMES can save heat leakage of 2.4 kW for a 200 kW system. Also, it was shown that immersing VSC SMES in 77 K increases the supply during load loss by 2%. In the end, an SVM algorithm was used that was able to identify fault conditions with high accuracy.

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