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Insulation Monitoring in Ungrounded Electrical System for More Electric Aircrafts

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***Abstract*—Electrification in transportation is gathering pace with several initiative like the more electric aircraft. In order to improve the availability of electrical power systems in aircraft applications, the use of an ungrounded IT system is proposed with the benefit of guaranteeing operation even in the case of a single insulation fault to ground. An insulation monitoring device is proposed to continuously monitor the insulation resistance and provide support for any preventative maintenance. Extensive simulations and experimental validations are presented to support the concept.**

Keywords—more electric aircraft, power systems, insulation, condition monitoring, reliability

I. INTRODUCTION

The requirement for increased efficiency, higher power density, and improved fuel economy of aircrafts has led to widespread electrification in aerospace industry. This has opened a new frontier for electric drives, motors and power electronics converters as the enabling technology in the initiative known as 'more electric aircrafts' (MEA) [1]–[3]. In conventional aircrafts, fuel combustion is used by the engine to produce the propulsion required for the flight and generate power for four main subsystems in the aircraft: the electrical system for powering loads such as the avionics, lighting and in-flight entertainment; the pneumatic system uses a bleed valve for providing cabin pressurization, air-conditioning and wing ice protection; the hydraulic system used for actuation systems; and mechanical system for oil pumping of the engine. However, the infrastructure required for these subsystems is bulky, inefficient and requires costly maintenance. Electrification promises to improve the overall efficiency and power density.

However, despite the benefits of electrification, the long term reliability of electrical systems in aircraft applications is still unproven. Components in onboard electric power system (EPS) are subject to thermal and environmental stress factors that accelerate degradation of insulation materials which can be accelerated by a number of factors for examples overvoltages generated by fast switching power electronics converters and partial discharge (PD) phenomena [4]. PD is particularly concerning in aircraft applications due to the decrease in partial discharge inception voltage (PDIV) at low ambient pressure in high altitude flights where the breakdown of air can occur at a voltage slightly above 300 V [5]. The probability of partial discharge has been found to increase on the surfaces of stacked PCB boards, edges of busbars, external connection terminals, triple points inside power modules and machines' winding insulation.

As the trend for MEA continues to grow, it is critical that these reliability issues associated with electrification of aircraft are addressed. An aircraft's EPS must guarantee continued operation even in the event of fault. However, the detection and localization of ground fault in the EPS of reliability critical application is a very challenging problem. To prevent the possibility of unscheduled shutdown during the occurrence of first ground fault in EPS, the ungrounded system without an intentional connection to ground, designated as "Isolation-Terre (IT) system" by IEC [10], is preferred for reliability critical applications such as power distribution in the operating theatre of hospitals. In IT systems, all active parts are insulated from earth or connected to earth through a high impedance. Due to the lack of a return path for current in the case of a fault, the fault current (determined by the insulation resistance and the system leakage capacitance) is usually very small hence the touch voltages of any exposed conductive body is very small and safe even in the case of a first fault to ground, significantly increasing the availability of the EPS which can operate indefinitely with a ground fault on one phase, eliminating the need for unscheduled shutdown [11]. However, due to the very small fault current, insulation failures in IT systems cannot be easily detected compared to grounded systems such as the Terre-Neutral (TN) and Terre-Terre (TT) systems. In TN and TT systems protective circuit breakers are needed to provide fast tripping of faulted circuits. IEC standards for terrestrial distribution systems, require the use of Insulation Monitoring Devices (IMD) to allow the identification of low resistance faults in IT systems.

Even though different topologies of IT systems are now becoming preferred candidates for marine electric system [12], DC traction [13] system, and have been accepted as a standard in industrial applications [14], not much attention has been paid to their application in aerospace. This work therefore proposes an innovative fault-tolerant IT system for aircrafts EPS with IMD to continuously monitor the insulation condition. Fig. 1 shows the how the proposed scheme is integrated into the architecture of more electric aircraft.

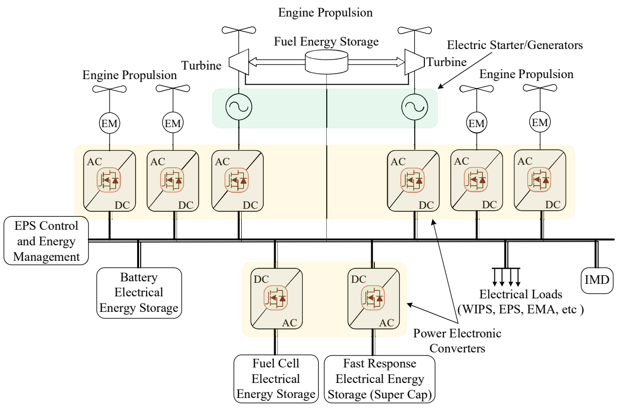


Fig. 1. The architecture of a more electric aircraft with IMD.

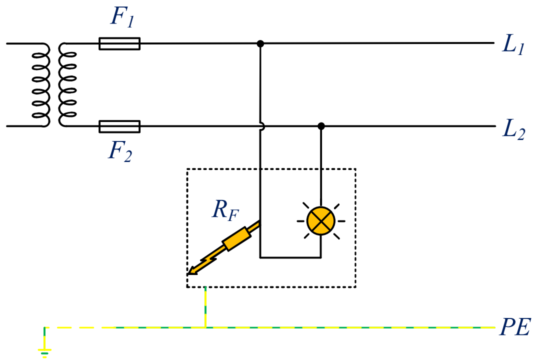


Fig. 2 A typical high-resistance IT system.

Extensive results of models and simulations which evaluate different conditions such as phase-to-ground fault, inverter phase-to-ground, in the EPS of an aircraft are presented to demonstrate the efficacy of the proposed scheme. The rest of the article is arranged as follows: Section II gives an overview of IT system type of grounding. Section III introduces the proposed system, describes the challenges associated with grounding an EPS, especially as it pertains to MEA, and how the IMD addresses these challenges for aerospace application and proves the feasibility of the concept. Section IV then reports the results of extensive simulations carried out using MATLAB Simulink while Section V concludes the article.

II. Ungrounded IT Systems for Aerospace

Grounding in an electrical system provides an electrical connection, typically indicated as protective earth (PE) between a conductive object and a conductive return path for the purpose of safety by bonding all exposed conductive surfaces to a ground potential. In TT and TN systems, the PE conductors are electrically connected to a terminal in the power supply, e.g. the star point of a distribution transformer or the negative of a DC power supply. This PE connection provides a return path for any fault currents, which can then trigger ground current circuit breakers.

As shown in Fig. 2, in IT systems there is no electrical connection of the PE conductors to the power supply, and therefore no fault current can flow in the event of a single fault to ground (PE). IT systems have the inherent advantage of being able to operate continuously with a ground fault on one phase, preventing the need for an unscheduled shutdown [11]. In the event of a fault between a line conductor and an exposed-conductive-part (ECP), only small fault currents can flow which are the result of distributed capacitance to ground in the system. These are generally too small to be dangerous to humans. This advantage offered by IT system is of great benefit to reliability critical applications and is commonly used in the operating theatre of hospitals, etc. [14], [15]. However, unlike its solidly grounded and independently grounded counterparts, the small ground fault current cannot trip protective devices, making fault identification and localization difficult in IT systems [16].

The continuity of service in the event of a fault makes IT systems superior to TN or TT systems, and therefore makes them preferable in reliability critical applications. However, despite their effectiveness and success in other transport and industrial applications, such as marine transportation [12], rail traction system [13] and petrochemical industry [14], IT systems have not found wide application in aircrafts' EPS. Existing standards for aerospace require a grounding topology that features the combination of neutral conductor and the protective earth in a single conductor (TN-C-S) for the grounding of aircrafts which is usually bonded to the aircraft body [17]. With the increasing use of carbon fibre reinforced polymer (CFRP) for aircraft structures due to its superior mechanical properties compared with metallic structure, the application of TN-C-S grounding topology in modern aircrafts has been shown to be problematic [18]. Due to its electrical non-conductivity, the CFRP structure can add impedance to the path of a ground fault which can result into a low electrical current that can inhibit the detection of incipient ground fault in an aircraft. This effect also, in the long run, causes Joule heating which can deteriorate the CFRP structure, and consequently compromise the overall structural integrity of the aircraft [18].

Therefore, the need for an advanced grounding solution with an effective fault ride-through capability for aerospace applications is essential. Accordingly, this work presents a grounding solution specifically developed for a more electric aircraft [19]. To fulfil the need for insulation monitoring in the system, an insulation monitoring device (IMD) that incorporates an alarm system is introduced [10]. The proposed scheme continuously monitors and records the insulation resistance value. The working principle of the proposed IMD is detailed in Section III.

III. Insulation Monitoring Device (IMD) for Aerospace

The proposed IMD is capable of monitoring different fault conditions that may occur an aircraft's power system irrespective of their location, including motor phase to ground insulation fault, inverter phase to ground insulation, DC bus insulation fault, etc. The principle of operation of the IMD is illustrated in Fig. 3 where the C_e and R_e denote the equivalent capacitance and equivalent resistance to ground, respectively, which are seen by the IMD and used in determining the health status of the insulation. The IMD injects a low frequency common-mode signal into the power system with respect to the PE and then measures the resulting leakage current returning through the IMD to determine the status of health of the insulation. Through the parasitic capacitances and insulation resistances, the leakage current finds its way to the IMD where calculations are performed to determine the state of health of the insulation. In the case of a healthy insulation, the fault resistance, in parallel with the parasitic capacitance, will have a very high ohmic value, i.e >10s of MΩ. In such a scenario, the impedance offered by the parasitics to ground will be mostly capacitive. The low frequency common mode signal injected by the IMD will have little or no effect on the leakage current as this will be dominated by the high frequency current components that are due to the common mode voltage excitation and conducted EMI's from the switching converters. If there is insulation fault at any locations, the impedance at the fault location will be dominated by the resistance in the lower frequency region while the impedance remains capacitive in the high frequency

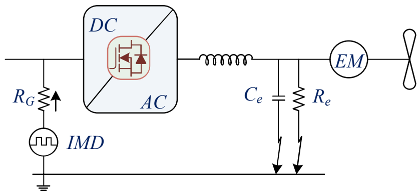


Fig. 3 The working principle of the proposed IMD.

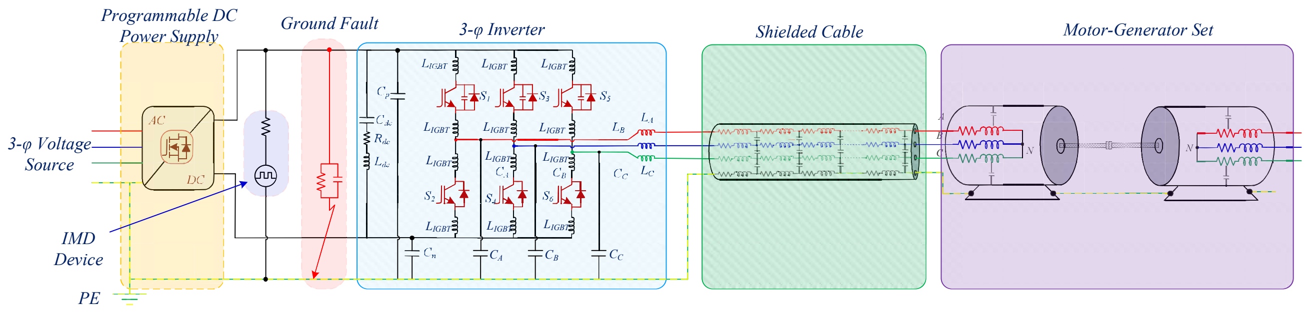


Fig. 4 Simulation model of the propulsion unit.

region. Due to co-existence of low frequency components due to common mode voltage from the IMD and high frequency component due to the common mode voltage components associated with switching of the inverter, the proposed system uses a low pass filter with an appropriate cut-off frequency to reject the high frequency component. Based on the amplitude of the low frequency current and the phase relation with the injected common mode voltage, the insulation resistance will be calculated to determine the insulation's state of health.

IV. Simulation Framework and Modelling Tool

To verify the proposed IT system and demonstrate its feasibility in aerospace application, a representative model of an aircraft's EPS was simulated using MATLAB Simulink to emulate the dynamics of an aircraft's EPS in the event of a ground fault. The simulated model, depicted in Fig. 4, features an exemplary architecture of a propulsion system based on [20]. For simplicity, but without losing generality, the architecture was implemented with one propulsion unit. Given the parallel between more electric aircraft and electric vehicles power conversion technologies [2], the parameters used in [21] for an automotive application were adopted and used in the simulation to emulate the dynamics of an aircraft's EPS which is under the effect of conducted EMI's. The model's equivalent circuit consists of a DC power supply, DC bus bar, common mode filter, IGBT-based inverter, AC bus bars and a permanent magnet motor.

In the model, resistances and inductances of DC positive and negatives lines are R_{DC+}, R_{DC-} and L_{DC+}, L_{DC-}, respectively, while their capacitances to ground are C_{DC+} and C_{DC-}. The DC link capacitor is C_{DC}, and the lead inductance and equivalent resistance of C_{DC} are R_{DC} and L_{DC}. The AC bus is formed by the resistances and inductances of three-phase lines R_{CA}, R_{CB}, R_{CC}, L_{CA}, L_{CB}, L_{CC}, and ground capacitances are C_{AG}, C_{BG}, C_{CG}. The phase resistances and inductances of the three-phase winding of the PMSM are R_{MA}, R_{MB}, R_{MC}, L_{MA}, L_{MB}, and L_{MC} while C_{MA}, C_{MB} and C_{MC} are the ground capacitance of the motor. The inverter bus-to-ground are C_P and C_N. The lead inductance of IGBT is L_{IGBT} and C_{S1}~C_{S6} represent the parasitic capacitances of the DC positive and negative for IGBT inter-electrode equivalent capacitances; the neutral point-to-ground parasitic capacitances of the three-phase bridges are C_A, C_B and C_C; the inductances of copper busbar connected by the neutral point of the inverter are represented by L_A~L_C. Table I shows the parameters used for the simulation.

V. Results and Discussion

Figs. 5 and 6 show the envelop of CM voltage and currents between the motor neutral terminal and ground when IMD is connected to the system. This envelop contains three main components, namely, 1.) low frequency (0.1-10s Hz)

TABLE I
HIGH-FREQUENCY CIRCUIT MODEL PARAMETER VALUES[21].

Parameter	Value	Parameter	Value
R_{DC+}, R_{DC-}	0.8 μΩ	L_{IGBT}	10 nH
L_{DC+}, L_{DC-}	32 nH	C_{S1} ~ C_{S6}	80 nF
C_{DC+}, C_{DC-}	900 pF	C_P ~ C_N	320 pF
C_{DC}	100 μF	C_A ~ C_C	500 pF
L_{DC}	90 nH	L_A ~ L_C	120 nH
R_{DC}	0.1 mΩ	R_{CA} ~ R_{CC}	0.52 mΩ
R_{MA} ~ R_{MC}	5.9 mΩ	L_{CA} ~ L_{CC}	26 nH
L_{MA} ~ L_{MC}	0.21 mH	C_{AG} ~ C_{CG}	672 pF
C_{MA} ~ C_{MC}	9nF		

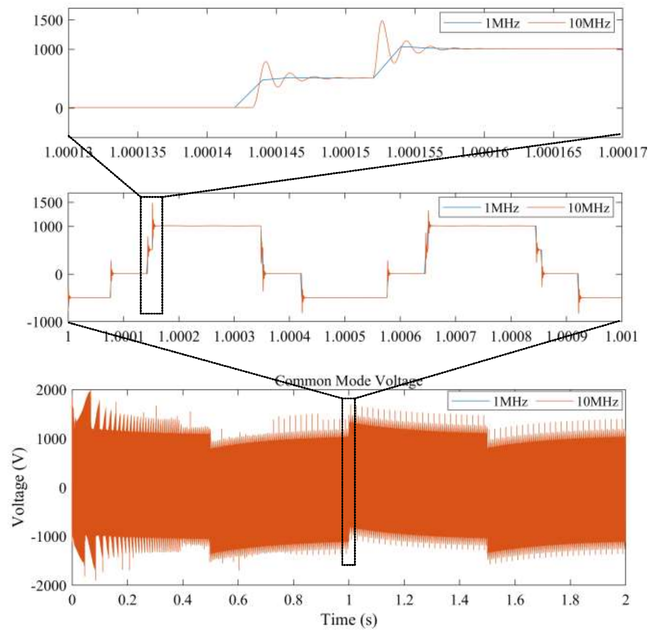


Fig. 5 Common-mode measured at the motor terminal when the IMD injects a low frequency signal.

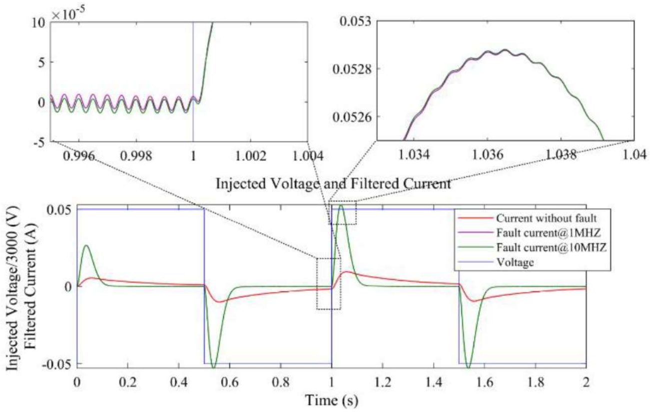
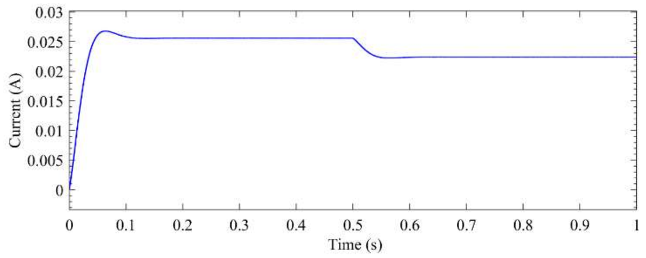
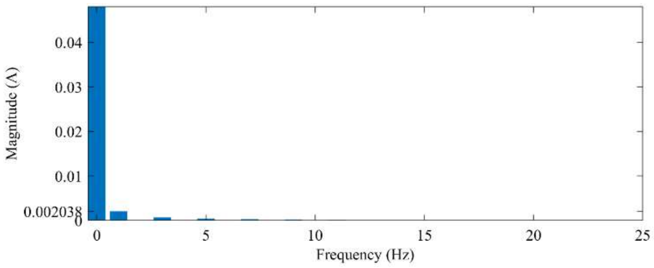


Fig. 6 Injected Common-Mode Voltage and Filtered Leakage Current.

associated with the injection frequency of the IMD; 2.) A component associated with the switching frequency of the converters (10s of kHz) due to the presence of non-zero CM



(a)



(b)

Fig. 7. IMD Measured low pass filtered current, (a) Time domain, (b) frequency domain.

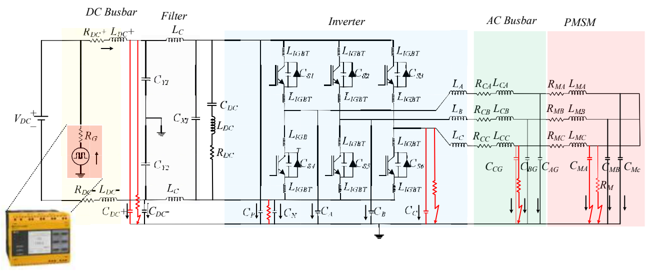


Fig. 8 Power system with insulation faults.

voltage of the converter; 3.) High frequency components associated with the instantaneous switching of the converter devices. This results in ringing with frequencies of 100kHz – 10s of MHz. It can be seen from the waveform how the high frequency components from the switching operation of power devices are superimposed on the low frequency components injected into the system by the IMD (in the 0.1-10Hz range). It can also be observed in Fig. 6 how the filtered current amplitude varies with different fault conditions due to different equivalent parasitic coupling between the element and ground. The leakage current will change for different fault conditions based on the equivalent resistance and the capacitance. This illustrates the necessity of a low pass filter with appropriate cut-off frequency to remove high frequency components, AC ripple corresponding to the fundamental frequency of motor as well as other low frequency components from differential mode and others that may be present in the system.

Fig. 7 shows the measured leakage current in the system with a motor phase to ground insulation fault after a low pass filter with 100 Hz cut-off bandwidth. The schematic of the system for this case is shown in Fig. 8. The corresponding ground resistance can be estimated as:

$$R_{estim} = \frac{Injected\ voltage\ (1Hz\ component)}{Filtered\ current\ (1Hz\ component)} \quad (1)$$

$$R_{estim} = \frac{63.66}{.002038} = 31236\Omega \quad (2)$$

Fig. 9 and 10 show a schematic and photos of an experimental test setup which will be used to practically demonstrate the operation of the IMD, while emulating typical operating

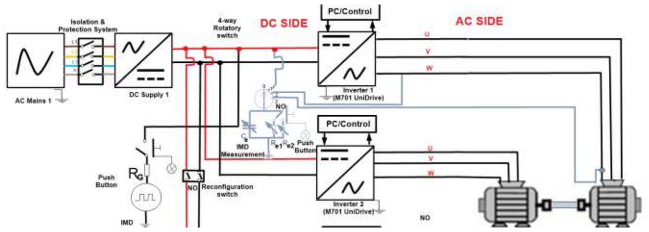


Fig. 9 Schematic of experimental rig for the proposed IMD system.

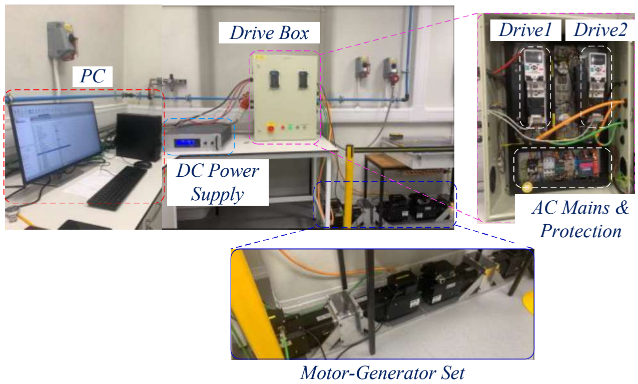


Fig. 10 Test setup for experimental validation of the proposed IMD system.

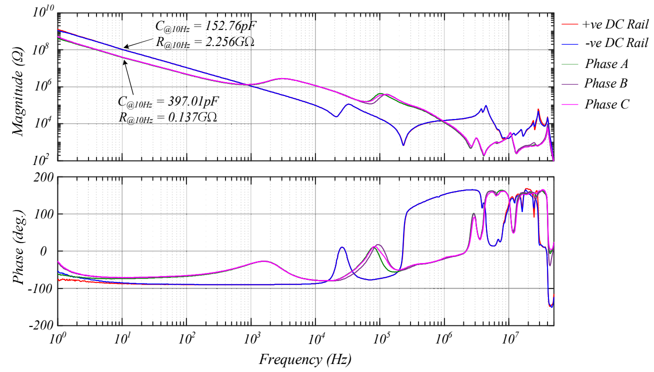


Fig. 11. Impedance to ground measured in several locations

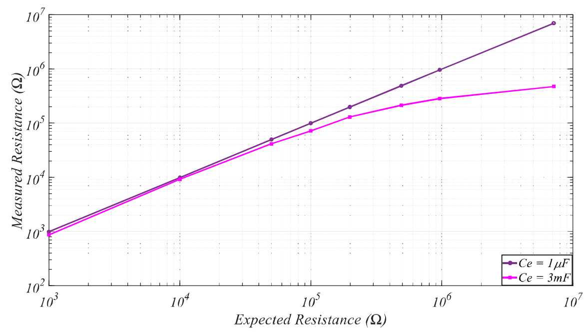


Fig. 12. Test results of IMD R_f measurement with different capacitances

conditions of a MEA EPS. The rig provides the possibility to emulate several fault conditions in various locations and with variable fault resistances and parasitic capacitances to ground in order to validate the modelling and tuning the IMD.

Fig. 11 shows the impedance to ground measured in the rig of Fig. 8 between the DC link and PE and between the motor terminals and PE. In all cases, it is shown that the low frequency resistance in healthy conditions is several hundreds of $M\Omega$. The effectiveness of IMD in detecting insulation ground faults by measuring the leakage resistance to ground, R_f, is shown in Fig. 12 The results show the measured resistances as a function of the artificially added ground fault resistance for two values of parasitic capacitances to ground. Although the accuracy of the system depends on the total network capacitance to ground, a great level of accuracy is demonstrated in most cases. A decrease in accuracy is shown for large ground capacitances and high resistances, e.g. $C_e = 3mF$. Nevertheless, parasitic capacitances in most practical power systems are expected to be significantly smaller, e.g. in the sub nanoFarad range, as measured in Fig. 11. It can be concluded that the IMD is able to measure the leakage resistance of representative electric power system of more electric aircrafts.

VI. Conclusion

The paper proposes the use of unearthed IT insulation system for use in more electric aircraft applications. The benefits in terms of increased availability due to the inherent ability to continue safe operation in case of first fault to ground are discussed. The use of an IMD to continuously measure the insulation resistance to ground is also proposed and validated through both simulation and experimental results on a test rig which emulates the typical operating conditions and all potential faults locations and severity in a typical MEA electrical power systems.

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References

[1] B. Wheeler, Pat; Sergei, “The More Electric Aircraft,” *IEEE Electrif. Mag.*, vol. 44, no. 0, pp. 6–12, 2014.

[2] K. Rajashekara, “Parallel between More Electric Aircraft and Electric\/Hybrid Vehicle Power Conversion Technologies,” *IEEE Electrif. Mag.*, vol. 2, no. 2, pp. 50–60, Jun. 2014, doi: 10.1109/MELE.2014.2312460.

[3] G. Buticchi, S. Bozhko, M. Liserre, P. Wheeler, and K. Al-Haddad, “On-board microgrids for the more electric aircraft - Technology review,” *IEEE Trans. Ind. Electron.*, 2019, doi: 10.1109/TIE.2018.2881951.

[4] S. Sundeep, J. B. Wang, A. Griffo, and F. Alvarez-Gonzalez, “Anti-resonance Phenomenon and Peak Voltage Stress within PWM Inverter Fed Stator Winding,” *IEEE Trans. Ind. Electron.*, vol. 0046, no. c, 2021, doi: 10.1109/TIE.2020.3048286.

[5] E. Husain and R. S. Nema, “Analysis of Paschen Curves for Air, N2 and SF6 Using the Townsend Breakdown Equation,” *IEEE Trans. Electr. Insul.*, 1982, doi: 10.1109/TEI.1982.298506.

[6] A. K. Morya *et al.*, “Wide bandgap devices in AC electric drives: Opportunities and challenges,” *IEEE Trans. Transp. Electrif.*, vol. 5, no. 1, pp. 3–20, 2019, doi: 10.1109/TTE.2019.2892807.

[7] J. M. Erdman, R. J. Kerkman, D. W. Schlegel, and G. L. Skibinski, “Effect of PWM inverters on ac motor bearing currents and shaft voltages,” *IEEE Trans. Ind. Appl.*, 1996, doi: 10.1109/28.491472.

[8] J. F. Ziegler, “Terrestrial cosmic rays,” *IBM J. Res. Dev.*, 1996, doi: 10.1147/rd.401.0019.

[9] H. P. Rimal *et al.*, “Protection from Indirect Lightning Effects for Power Converters in Avionic Environment: Modeling and Experimental Validation,” *IEEE Trans. Ind. Electron.*, 2021, doi: 10.1109/TIE.2020.3013794.

[10] IEC, “IEC 60364-4-41:2005+AMD1:2017 CSV Low voltage electrical installations - Part 4-41: Protection for safety - Protection against electric shock,” *International Standard*, 2017. .

[11] T. Baldwin, F. Renovich, L. F. Saunders, and D. Lubkeman, “Fault locating in ungrounded and high-resistance grounded systems,” *IEEE Trans. Ind. Appl.*, vol. 37, no. 4, pp. 1152–1159, 2001, doi: 10.1109/28.936408.

[12] A. M. Bruning and E. W. Lusby, “Advantages of ungrounded marine electric systems,” *Trans. Am. Inst. Electr. Eng. Part II Appl. Ind.*, vol. 79, no. 5, pp. 348–363, 1960, doi: 10.1109/TAI.1960.6371582.

[13] J. Do Park, “Ground fault detection and location for ungrounded DC traction power systems,” *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5667–5676, 2015, doi: 10.1109/TVT.2015.2388785.

[14] J. P. Nelson and P. K. Sen, “High-resistance grounding of low-voltage systems: a standard for the petroleum and chemical industry,” *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, pp. 941–948, 1999, doi: 10.1109/28.777204.

[15] D. H. Lubich, “High resistance grounding and fault finding on three phase three wire (delta) power systems,” 1997, doi: 10.1109/texcon.1997.598534.

[16] E. B. Joffe and K. S. Lock, *Grounds for Grounding: A Circuit-to-System Handbook*. 2010.

[17] U.S Department of Defense, “MIL HDBK 274A Electrical Grounding for Aircraft Safety,” *MIL HDBK 274A Electrical Grounding for Aircraft Safety*. 2011.

[18] C. E. Jones *et al.*, “Electrical and Thermal Effects of Fault Currents in Aircraft Electrical Power Systems with Composite Aerostructures,” *IEEE Trans. Transp. Electrif.*, 2018, doi: 10.1109/TTE.2018.2833838.

[19] IEEE, “IEEE Recommended Practice for System Grounding of Industrial and Commercial Power Systems,” *IEEE Std 3003.1-2019*. pp. 1–79, 2019, doi: 10.1109/IEEESTD.2019.8793247.

[20] “Airbus, Rolls-Royce and Siemens develops Hybrid-Electric demonstrator - Leeham News and Analysis,” *[Online]*, 2019. https://leehamnews.com/2017/11/29/airbus-rolls-royce-siemens-develops-hybrid-electric-demonstrator/ (accessed Dec. 15, 2022).

[21] L. Zhai, G. Hu, C. Song, M. Lv, and X. Zhang, “Comparison of Two Filter Design Methods for Conducted EMI Suppression of PMSM Drive System for Electric Vehicle,” *IEEE Trans. Veh. Technol.*, 2021, doi: 10.1109/TVT.2021.3080924.