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Electrical and Electronic Technologies in More-Electric Aircraft: A Review

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ABSTRACT This paper presents a review of the electrical and electronic technologies investigated in more-electric aircraft (MEA). In order to change the current situation of low power efficiency, serious pollution, and high operating cost in conventional aircraft, the concept of MEA is proposed. By converting some hydraulic, mechanical, and pneumatic power sources into electrical ones, the overall power efficiency is greatly increased, and more flexible power regulation is achieved. The main components in an MEA power system are electrical machines and power electronics devices. The design and control methods for electrical machines and various topologies and control strategies for power electronic converters have been widely researched. Besides, several studies are carried out regarding energy management strategies that intend to optimize the operation of MEA power distribution systems. Furthermore, it is necessary to investigate the system stability and reliability issues in an MEA, since they are directly related to the safety of passengers. In terms of machine technologies, power electronics techniques, energy management strategies, and the system stability and reliability, a review is carried out for the contributions in the literature to MEA.

INDEX TERMS More-electric aircraft, machine technologies, power electronics techniques, energy management strategies, system stability and reliability.

I. INTRODUCTION

With the purpose of reducing the fuel consumption, operating cost, and noise of aircraft, the concept of more-electric aircraft (MEA) emerges and substantial efforts have been made in this area. The intrinsic feature of MEA is converting the traditional hydraulic, mechanical, and pneumatic power sources into electrical ones. For conventional aircraft power systems, in order to expand or compress the air for cabin pressurization and temperature regulation to make the passengers feel comfortable, pneumatic power, which is created by bleed air, is used to turn turbomachinery. In addition, hot air is supplied, which plays an important role in de-icing for the wings of an airplane. Besides, by using gearboxes, the mechanical power is transferred from main engines to central hydraulic pumps for flight controls and landing gear, and to electric generators for electrical distribution in engine systems and commercial loads [1]. High power density and robustness are obtained for the hydraulic power subsystems, while they are heavy and inflexible [1]. In a conventional aircraft, a highly centralized on-board electrical power distribution system (EPDS) architecture is presented to connect all the individual power bus rails, where the long distances of power distribution networks result in significant power losses and increase in weight. On the contrary, remote power distribution units are installed in MEA to place the power supply closer to loads. The system power distribution architectures for both conventional aircraft and MEA are shown in Figure 1.

It can be seen from Figure 1(a) that the centralized power system distribution structure is applied, which is detrimental for remote power distribution. In the relatively new types of airplanes such as Boeing 787 and Airbus A380, an increasing

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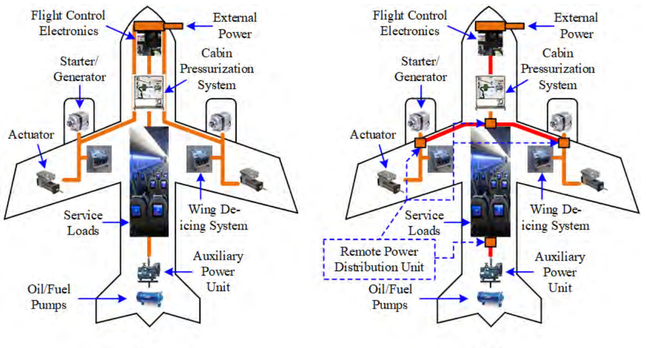

(a) (b)

FIGURE 1. **Layout of system power distribution in (a) a conventional aircraft and (b) an MEA.**

use of EPDS is realized by applying a remote power distribution structure, as shown in Figure 1(b), which caters to the main features of an MEA.

In a traditional aircraft, the power generation, distribution and consumption for the electrical, pneumatic, hydraulic and mechanical systems are accomplished separately. In other words, there is no intrinsic interconnection among these subsystems. To be more specific, the power for avionics systems, lighting, and in-flight entertainment is supplied by the electrical source; the pneumatic system is responsible for providing power for wing de-icing, cabin pressurization, and air-conditioning; fuel and oil pumping are powered by the mechanical system; the power supply to the actuation systems for flight control and auxiliary services is from the hydraulic system. This kind of EPDS architecture limits the flexibility in power regulation, and it results in higher fuel cost and increased overall weight.

With the utilization of MEA concept, all the on-board loads are required to take power from an EPDS [2], [3]. Engine-driven generators are applied to provide electrical power for all the aforementioned loads. The key technology for realizing the MEA architecture is power electronics, which is necessary for the aircraft to adopt different voltage standards [3]. In this case, some of the pneumatic, mechanical and hydraulic systems are converted into electrical ones, which reduces the overall weight, cost, and environmental impact. In addition, owing to the elimination of pneumatic system, the efficiency of compressor is greatly improved since there is no need to have a bleed air system. As the technology of MEA develops, minimized mechanical linkages and hydraulic power supply networks are obtained, which reduces the complexity in maintenance [4]. Moreover, by employing electrical systems for supplying the majority of on-board power, the times of unscheduled maintenance can be reduced as more options for reconfigurability and advanced prognostics and diagnostics are available [3]. Furthermore, the future aircraft is becoming quieter and more fuel efficient by adopting the MEA concept [3].

In a traditional civil airplane, the 115V line-to-neutral AC voltage and stable line frequency of 400Hz are applied in the EPDS [2]. While in an MEA, to achieve lighter weight for the generator system, 230/400Vac, 400Hz is a commonly adopted option. As an alternative, a variable bus frequency between 350 and 800Hz according to the changes in the engine speed with the voltage regulated at 115 or 230Vac can be adopted, which increases the reliability of the whole system [2], [3]. Moreover, there are 28Vdc loads on an MEA, where the 28V DC voltage is derived by converting the 115Vac, 400Hz with the application of transformer rectifier units [2], [3].

There are several review works on MEA carried out previously by other researchers. In [4], an overview of motor drive technologies for MEA was presented. It mainly focused on motor design and the choice of motor drive, but the system-level studies were neglected. In addition, the review work in [5] discussed the main technologies adopted for electric power generation over a hundred years' time span, without mentioning the techniques used in other subsystems. On the other hand, from the system level, [2] reviewed the state-of-the-art technology for power conversion in large commercial transport aircraft from the aspects of major subsystems. However, all the reviewed works were conducted before 2015. In [6], only the thermal load analysis and thermal management for hydraulic system in MEA were concerned. Moreover, the selection of electric power system architecture for future MEA according to weight-saving criterion and stability features was investigated in [7]. Furthermore, the load management and advanced control strategies for on-board microgrids for MEA were highlighted in [8], while the investigations on motor technologies and energy storage were not discussed. All the above mentioned review papers fail to comprehensively reveal the latest developments in MEA from both the powertrain and power system levels.

This paper aims to review the electrical and electronic technologies applied in MEA, illustrate the contributions of the research activities in this field, discuss the pros and cons of each method, and finally present the open challenges and opportunities in the development of MEA EPDS. Most of the research works reviewed are within the recent 5 years. At the powertrain level, the two types of most critical power components, namely electrical machines and power electronics devices, will be studied in detail. On the other hand, at the power system level, several studies focused on the energy management strategies (EMS) and system stability and reliability issues, aiming at obtaining superior system performance. Therefore, the machine technologies, power electronic techniques, EMSs, and system stability and reliability will be respectively reviewed from Sections II to V. The divisions of the main research interests in the literature for these 4 subsections are implemented in Figure 2, which also shows the structure of this paper. Finally, a conclusion will be given to summarize all the key points obtained in the literature and discuss the open challenges and opportunities to guide the future research on the electrical and electronic technologies of MEA.

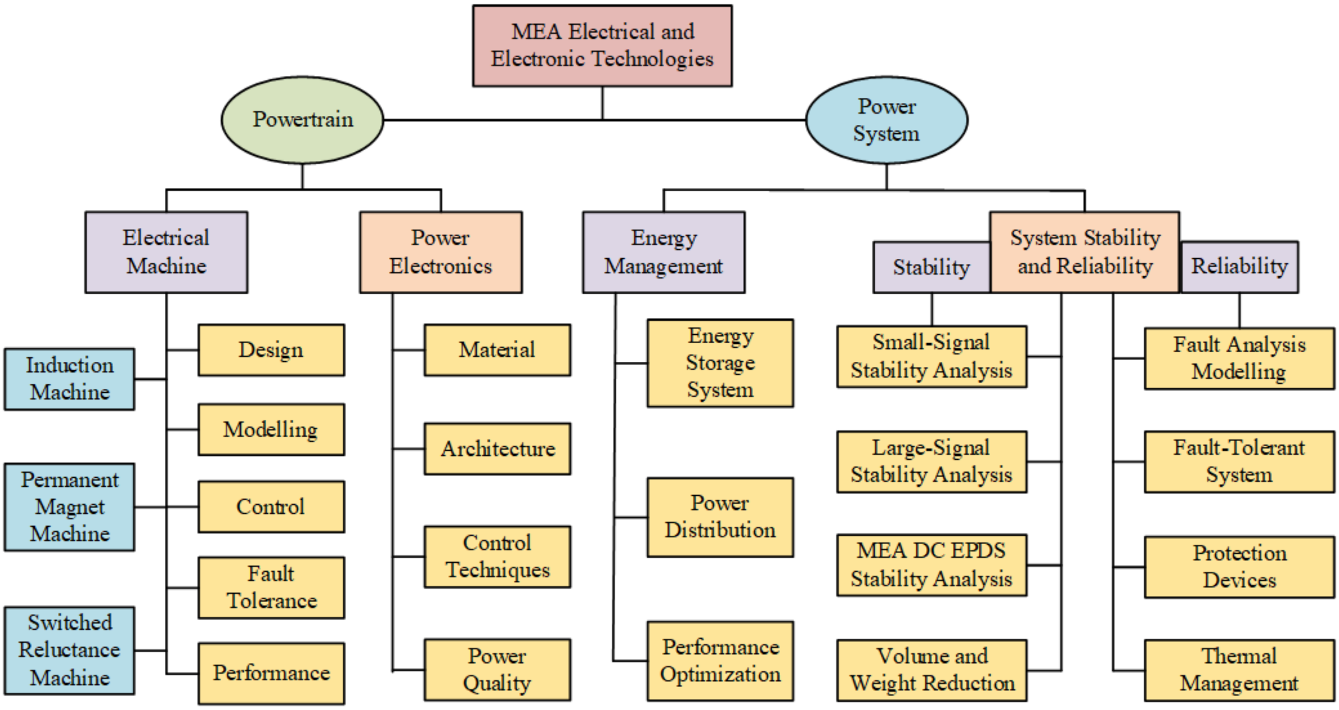

FIGURE 2. Classification of the main research interests in MEA electrical and electronic technologies.

II. MACHINE TECHNOLOGIES

In the past few decades, a number of researches have been carried out regarding the machine technologies used in MEA. Different electrical machine topologies for electric aircraft propulsion were compared in [9] by considering the trade-offs in the power electronics, fault response equipment, and gearbox components. It was discovered that permanent magnet synchronous machines (PMSMs) have outstanding power density. In addition, when additional drive and fault response components are taken into consideration, PMSMs still maintain the weight advantage. The authors in paper [4] mainly focused on choosing the candidate machines along with their drive topologies in MEA applications. Since the aircraft applications put forward specific rigorous requirements for power density, reliability and availability on electrical machines, three types of electrical machines applied on aircraft developed rapidly in recent years, which are the induction machines (IMs), PMSMs, and switched reluctance machines (SRMs). In case the readers are not familiar with the machine design and basic working principles of these electrical machines, they are suggested to refer to [10]–[12].

A. IM

In [13], [14], an induction generator (IG) based AC-DC hybrid EPDS for MEA was illustrated, and the constant-voltage variable-speed power was directly supplied from the generator terminals by omitting external exciters. The problem of excessive fault current caused by permanent magnet (PM) excitation was solved in the proposed system. By maintaining the advantages of the DC primary generation configuration, the undesired AC-DC-AC power conversion is eliminated. However, a lower system integration level and decreased power sharing capability are presented.

In addition to squirrel-cage IMs, a doubly-fed induction generator (DFIG), which is a wound-rotor IM, can be integrated in aerospace power systems [15]. The fractionally rated converter between the rotor and grid makes this type of power generation system attractive. On top of that, owing to lower maintenance cost and higher reliability than conventional DFIG, a cascaded DFIG (CDFG) was applied in [16] for aircraft starter/generator. A reduced-order model of CDFG was proposed to simplify the resistance and dependent voltage source in the rotor loop, therefore making the analysis procedure easier. On the other hand, the applications of these types of IMs are limited to the scenarios where the speed range is narrow.

High fault tolerance is critical for the reliable operation of IMs in MEA applications, and multi-phase IMs represent one of the most promising approaches to enhancing IM fault tolerance. In [17], an enhanced predictive current control technique with a fixed switching frequency was proposed for an asymmetrical six-phase IM drive, which is composed of two three-phase AC drives. The new control strategy called "enhanced finite set model predictive control" proposed in [17] considered the use of predictive and modulation schemes for the current control, and the performance of the motor drive was improved by searching the best distribution of the switching losses. Besides, the overload capabilities and post-fault operations of an asymmetrical shaft-line-embedded six-phase IM were verified in [18] by a direct-flux vector control scheme based on a double-stator approach. Nevertheless, these strategies all increase the system complexity and cost, and they have limited applications.

B. PMSM

Owing to the characteristics of high power density, high efficiency, high torque/inertia and torque/volume ratios, fast dynamic response, and high reliability, PM machines are widely used for MEA applications.

In a traditional 3-stage brushless generator excitation system, the PM machine is usually utilized as a pre-exciter. The design methodology of an outer pole stator PM machine was presented in [19], which replaced the main exciter's stator field winding with PMs, and the excitation system was modified to be a 2-stage one. This design method brings about a high response speed, fault ride-through capability and reduced quantity of components, while a lower power factor, smaller per unit synchronous reactance, and downscaled rating are the demerits. In [20], a fault-tolerant five-phase PM motor drive was developed for an aircraft flat actuator application, which realized sensorless control. In the proposed fault-tolerant strategy, the load specifications can be satisfied when one or two phases are open-circuited, or a short-circuit fault in one phase is encountered. While redundant phases and power modules are used, making the system more complex.

In order to improve the system reliability to overcome position sensor failure, the sensorless operation of a PM synchronous generator (PMSG) for aircraft was investigated in [21]. The applied voltage is obtained in the sensorless control technique directly from the machine current waveforms. The two control variables of current magnitude and power factor angle are applied, and a lower level of complexity is presented compared with the traditional method by utilizing *dq* variables. However, the system efficiency is sacrificed, and it is less tolerant to overmodulation. The overall control structure for sensorless PMSG generation system is displayed in Figure 3.

In [22], a sensorless rotor position estimation scheme by using high frequency signal injection (HFI) was presented for IPMSM. The frequency and amplitude of injected high frequency signal were optimized by considering different operation conditions. In addition, with the consideration of power switch open circuit fault and phase current sensor failure in the motor drive, the HFI sensorless control strategy was carried out for IPMSMs to ride through hybrid faults in [23] with motor drive reconfiguration. Moreover, a winding-based discharge mechanism was proposed in [24] to swiftly discharge the DC-bus capacitor in a PMSM drive system to avoid electric shock after accidents. The large rotor inertia and low safe current were taken into account for designing the control algorithm, which inspires researchers to pay attention to the electric safety issues in MEA motor drive systems.

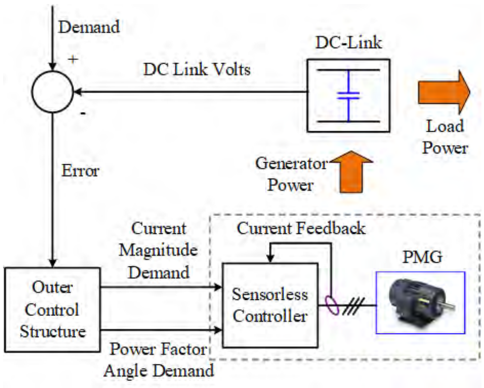

FIGURE 3. Overall control structure for sensorless PMSG generation system [21].

With the target of increasing the reliability of MEA power system, the fault-tolerant control of a PMSG-fed AC-DC drive rectification system was obtained in [25]. The variable-speed multi-spool direct drive architecture with a DC distribution bus was investigated in [25], where the minimum reactive power transfer and reduced overall copper losses are obtained, but transient surge currents and the risk of converter failure are inevitable. In addition, the fault-tolerant operation of five-phase PMSM drive was investigated with short-circuit inverter fault, one phase loss, and third-harmonic current injection in [26]–[28], respectively. Furthermore, a novel ten-phase fault-tolerant PMSM with two stators and two rotors on the same shaft was proposed in [29], and a novel speed control scheme of the developed motor was presented by considering the electromagnetic torque ripple in the fault switch process. In [29], the PMSM with multiple single-phase windings was selected, and the uniform boundedness and uniform ultimate boundedness of the system were ensured by the proposed fault-tolerant control strategy. Good performance in the fault switch process and good robustness to load disturbance and parameter variations are also presented. However, the circuit topology is complicated, and high-frequency oscillation of speed trajectory exists.

C. SRM

Owing to relatively good performance of SRM under the conditions of high temperature and mechanical stress, a substantial number of relative researches were conducted.

A new type of SRM with modular stator that applies to safety critical applications was proposed in [30]. For a multiphase modular stator, a magnetic coil winds on each separated stator segment independently, which means the faulty coils can be replaced without decoupling the stators from the loads. The structure of stator is simplified in this case, and the iron loss of SRM is reduced by simplifying the paths of magnetic flux, while significant torque ripples occur. Moreover, an extended magnetic operating region and greater torque were derived for an SRM by placing magnets in the stator slot opening in [31] to obtain a PM assist segmented rotor SRM (PMA S-SRM) topology for fault tolerant aerospace applications. 21% of torque increase was predicted when comparing to the magnet free S-SRM. However, the efficiency is low, and the safe areas for PM need to be carefully selected.

SRMs are also applied as generators for MEA, in which case they are called switched reluctance generators (SRGs). In [32], the detailed design of a high speed SRG was put forward and the performance of the prototype was verified and optimized, and a wide torque-speed envelope is presented in the motoring mode. Additionally, a high speed SRG drive was proposed in [33] with the electromagnetic design, power electronics design, and thermal model developed by adopting a 6/4 SRG and a half-bridge per phase converter. Moreover, in [34], a new high speed SRG drive with a wide constant power speed range was accomplished by designing a new rotor structure, with the measured efficiency of the developed drive reaching 82% at the peak torque conditions, while it is only applicable in the starting mode, with several mechanical limitations.

High torque ripple and acoustic noise are the main drawbacks for SRM, therefore a number of efforts were made to improve the performance of SRM from these two aspects. In [35], a review on torque ripple minimization techniques for SRM was carried out, which pointed out that between the two approaches, machine magnetic design and electronic control, the latter is more cost-effective and flexible in reducing the torque ripple. Meanwhile, from the viewpoints of motor topology optimization and control strategy improvement, a detailed analysis on the radial and tangential forces was conducted to explain the mechanism of the SRM noise in [36], and a comprehensive review of the state-of-the-art techniques on mitigation of radial vibration and torque ripple was presented for acoustic noise reduction. In addition, a novel family of torque sharing functions (TSFs) were proposed in [37], and the optimal TFS was selected to present a much lower communication torque ripple ratio in both linear and saturation magnetic region. A new direct torque control (DTC) strategy with no flux control and less negative torque was proposed in [38]. The electrical space sectors were reorganized, and vector reform was implemented to mitigate the instantaneous negative torque. By applying the proposed method, the torque ripple can be decreased from 38.33% to 16.67%, and the torque-ampere ratio can be increased by over 18.43%, when compared with the traditional DTC method.

In [39], an accurate fault identification method of power converter in SRM was presented to minimize the influence of faults on the generator. In this technology, the phase currents are easily obtained from the main control system without adding extra sensors, which avoids analyzing the effects of load level, rated power and mechanical speed. The algorithm can effectively identify the type of fault and the affected inverter phase simultaneously, while an open-circuited insulated gate bipolar transistor (IGBT) may not be localized during the phase demagnetization process. Besides, the authors in [40] investigated a dual-channel SRM of a generator system and analyzed its performance. A speed closed-loop control strategy for motor mode and a voltage closed-loop control strategy for generator were presented to improve fault tolerance. Furthermore, a new fault-tolerant topology of SRM drive system was proposed in [41] for MEA and automotive applications. A relay network based on the conventional asymmetrical half-bridge power converter with four additional power switches was applied, and the fault diagnosis was accomplished by an HFI method. No additional sensor is required, and a wide range of mechanical operating conditions is presented.

D. SUMMARY

It can be seen that PMSM and SRM are widely adopted as the electrical machines for MEA. The design and control of these machines mainly focus on increasing the fault tolerance, as presented in [20]–[23], [25]–[30], [39]–[41], and multiphase machines represent a key developing trend. The details of the theme, merits and demerits of the machine technologies investigated for MEA IMs, PMSMs, and SRMs in the above mentioned works are illustrated in Tables 1, 2 and 3, respectively.

III. POWER ELECTRONICS TECHNIQUES

The development of power electronic techniques plays a significant role in the future aircraft applications, where AC and DC types of loads coexist. According to [42], in order to simplify the structure of MEA and reduce the weight, the hydraulic systems will be replaced by variable-speed generators along with power electronic devices.

A. MATERIALS

MEA is one of the critical industrial applications that requires operation with high temperature and high power, in which case the traditional Si-based power electronic converters are not likely to meet the requirements easily. By adopting the wide bandgap (WBG) semiconductor devices based on gallium nitride (GaN) and silicon carbide (SiC), the power electronic converters can operate normally in the harsh environment with the temperature over 200°C without employing external cooling [43]. Once the WBG semiconductor technology is sufficiently developed, the overall performance of MEA will be increased to a much higher level. Currently, the development of WBG semiconductors is still at the research stage, including design, fabrication, testing and control.

Aiming at high reliability and low weight, a 1.2kV SiC metal oxide semiconductor field effect transistor (MOSFET) was designed and experimentally tested for a three-phase buck-type pulse-width modulation (PWM) rectifier for aircraft power networks in [44]. Very stringent requirements can be met by presenting unity power factor operation and a very high-quality input current within the aircraft standard specification, and no excessive large filters are required. Besides, focusing on the highest power per weight, a design methodology for a high power density converter (HPDC) with high fault tolerance was proposed in [45],

TABLE 1. IM technologies for MEA.

Research Field	Reference	Theme	Merits	Demerits
Performance Analysis	[13, 14]	IG-based AC/DC hybrid generation system	1. Reduced hardware requirement 2. Good regulation of both AC and DC output voltages	1. Lower system integration level 2. Decreased power sharing capability
	[15]	Converter sizing for DFIG system	1. Reduced converter rating 2. Wide speed range with minimal additional power components	1. Low power density 2. Limited application scenarios
Modelling	[16]	Reduced-order model for stand-alone CDFG	1. Lower maintenance cost 2. Higher reliability 3. Easy analysis for CDFG	1. Complicated system structure 2. Only applicable in the case of synchronous reference frame
Control	[17]	EFSMPC for an asymmetrical six-phase IM drive	1. A lower mean square error of current components 2. Lower stator current harmonic components	1. High system complexity 2. A proper time scale needs to be selected
	[18]	Double-stator approach based direct-flux vector control scheme for an asymmetrical IM	1. High overload capability in both generation and motoring modes	1. The performance is greatly related to the accurate modelling and current limit calculations

TABLE 2. PMSM technologies for MEA.

Research Field	Reference	Theme	Merits	Demerits
Design	[19]	Design, characterization, and prototyping of a rotating brushless PM exciter	1. Fast response speed 2. Better fault ride-through capability 3. Reduced number of rotor slots	1. Lower power factor 2. Smaller per unit synchronous reactances 3. Downscaled rating
	[20]	Fault-tolerant design of a five-phase PM motor drive system	1. Run up to rated torque with one or two phases open 2. Sensorless capability	1. Redundant phases 2. Redundant power modules 3. High system complexity
Control	[21]	Power factor angle control based sensorless strategy for a hybrid PM generator	1. Operate the generator close to an optimum point 2. High reliability and less system complexity	1. Less tolerant to overmodulation 2. Reduced efficiency 3. More complicated demand and control signal relationship
	[22]	HFI based sensorless control for IPMSM	1. Accurate position estimation in different operation conditions 2. Good standstill and low-speed performance	1. Difficult to achieve both high estimation accuracy and low vibration, noise and losses.
	[23]	HFI based sensorless control for a TPFS inverter fed IPMSM with a single current sensor	1. Low system cost 2. High fault tolerance level 3. Excellent current and position tracking performances at low speed	1. High switching speed and switching losses 2. Not efficient at high speed
	[24]	Capacitor voltage discharge for PMSM drive using windings	1. Cost-effective 2. Fast discharging process	1. Limited by system parameters
	[25]	Control of a fault-tolerant PMSG-fed AC-DC active rectification system	1. Minimum reactive power transfer 2. Reduced overall copper losses	1. Transient surge currents 2. Risk of converter failure
	[26]	Behavior analysis of an open-end five-phase PMSM under inverter fault conditions	1. Without additional components 2. Constant torque operation	1. Speed limitation when the voltage constraint is important 2. High torque ripple
	[27]	Current control strategy for a five-phase PMSM with one phase loss	1. Simultaneously desirable power density, fault tolerance and robustness	1. Third harmonics exist 2. Limited to a specific type of fault
	[28]	Reduced-order matrices including first and third frame for five-phase PMSM with single-phase open-circuit fault	1. Reduced torque ripples 2. Fast dynamic response 3. Arbitrary open phase	1. High complexity in control algorithm 2. The transfer matrix has to be updated for different open phase scenario
	[29]	Robust control of a novel ten-phase fault-tolerant PMSM	1. guaranteed uniform/uniform ultimate boundedness of the system 2. Good performance in the fault switch process 3. Good robustness to load disturbance and parameter variation	1. Complicated circuit topology 2. High-frequency oscillation of speed trajectory exists

with a prototype of a 50kVA 2-level 3-phase SiC inverter operating at 60kHz switching frequency demonstrated, whose gravimetric power density achieves a high level of 6.49kW/kg.

For the sake of filling in the research gap of designing a compact *LCL* filter for HPDC with the considerations of size and thermal effects under high-power and high-switching-frequency situations, a comprehensive design flow of

TABLE 3. SRM technologies for MEA.

Research Field	Reference	Theme	Merits	Demerits
Design	[30]	Fault-tolerant modular stator SRM design	1. Simple construction 2. Uncoupling of the machine from the load is not needed 3. High efficiency with multiple opened coils.	1. Significant torque ripple 2. Detrimental high torque value to the overall performance
	[31]	PMA S-SRM for aerospace application	1. Increased torque 2. Improved fault tolerance to phase open and short circuit fault conditions	1. Low efficiency 2. The safe areas for PM have to be carefully selected
	[32]	Electromagnetic and thermal design of a high speed SRG	1. Wide torque-speed envelope in the motoring mode	1. No superior performance
	[33]	Selection of appropriate SRM drive topology for a high speed DC distribution grid	1. Higher design accuracy 2. Comprehensive consideration of different models	1. Complexity in modelling 2. No in-depth results available
	[34]	Design and initial testing of a high-speed 45-kW SRG drive	1. Very wide constant power speed range	1. Only applicable in starting mode 2. Several mechanical limitations
Control	[37]	Minimization of SRM torque ripple by a novel TSF	1. High drive efficiency 2. High torque-speed capability	1. Low torque ripple only with suitable values of constants in the objective function
	[38]	A new DTC for SRM by three improvements	1. Reduced torque ripple 2. Instantaneous negative torque greatly removed 3. Increased torque-ampere ratio	1. New voltage vector selection rule has to be created 2. phase current not enough for torque production
Fault Tolerance	[39]	A new real-time diagnosis algorithm of power converter faults in SRM drives	1. Reduced system complexity and costs 2. Simplified implementation 3. Effectively detect IGBT open- and short-circuit faults	1. May not localize an IGBT with open-circuit faults during the phase demagnetization process
	[40]	Improved fault tolerance for a dual-channel SRM	1. Great fault-tolerant capacity 2. More stable performance	1. Lower power density
	[41]	A new fault-tolerant topology of SRM drive system	1. No additional sensor 2. Wide range of mechanical operating conditions	1. Four additional power switches

LCL filter for a 50-kW, 60-kHz two-level SiC inverter was presented in [46] with a systematic evaluation of the tradeoff among the air gap, inductor weight, and thermal issue. The thermal requirement is met at full-load 50kW power, but with high inverter current harmonics. In addition, a prototype of 50-kW SiC three-phase VSI operating at a switching frequency up to 100kHz and a narrow dead band of 250ns for aerospace application was demonstrated to have a gravimetric power density of 26kW/kg without including a filter in [47]. An improved gate assist circuit (GAC) is used to provide a local low impedance discharging path. Although there is little improvement in efficiency (0.11%), the converter power loss reduction (5%) is significant.

In an MEA, the 28 and 270 V DC voltages are the two common bus voltage levels for supplying power to low-power on-board DC equipment, and a GaN-based battery charger topology with dual-output terminals was developed in [48] to operate as an LLC converter in the 28V mode and as a buck converter in the 270V mode. Zero-voltage switching (ZVS) can be realized for both modes to reduce the switching loss, and high power density is achieved for the power stage that includes all the printed circuit boards (PCBs) and heat sinks. However, the performance at high switching frequencies in buck mode is deteriorated, and a lower efficiency in LLC mode is presented in the full-load condition. Moreover, targeting at the 800Hz AC system and 600V level DC link in aircraft applications, a GaN-based Vienna-type rectifier with SiC diodes was proposed in [49]. The analysis on the voltage distortion due to the output capacitances of SiC and GaN devices was conducted, and a robust compensation scheme based on a pulse-based turn-off voltage error model was presented. Therefore, early determination of circuit parameters can be accomplished in the design process.

B. ARCHITECTURE

Three-phase power factor correction (PFC) rectifiers of several kilowatts are necessary for MEA to get better power conversion performance. In order to reduce the switching, sensing and control requirements, a three-phase buck-boost derived PFC converter with inductors connected in delta configuration was presented in [50]. Only three switches are required in the proposed architecture, and only one output voltage sensor is needed, instead of five in a conventional PFC converter, as the output voltage is regulated by a simple voltage control loop. Further analysis and detailed converter design calculations were given in [51], and the developed prototype achieves a low input current total harmonic distortion (THD) of 2.76% and a high efficiency of 96%. While the output filter has to be large enough to keep the output voltage constant. The proposed three-phase buck-boost derived PFC converter with AC inductors connected in delta configuration is shown in Figure 4.

Dual-active-bridge (DAB) converters are commonly applied for MEA application due to the intrinsic feature of

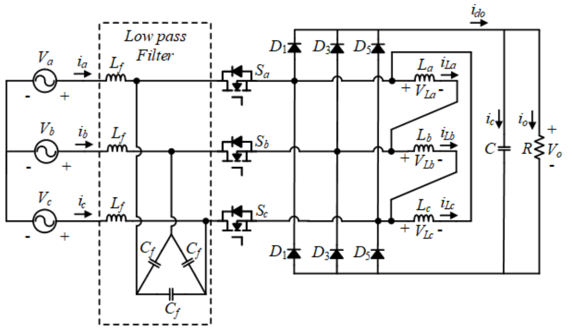

FIGURE 4. **The proposed three-phase buck-boost derived PFC converter with AC inductors connected in delta configuration [50], [51].**

ZVS commutation in a wide operating rage with low level of control system complexity. Alternatively, a current fed solution named the active bridge active clamp (ABAC) converter can also be applied. In [52], the comparison between DAB and ABAC converters for the specific application of a 270V/28V 10kW bidirectional DC/DC converter was carried out regarding the efficiency, weight, and volume. It was demonstrated by experimental verification that the ABAC converter can reduce the converter weigh and volume at high power ratings without decreasing the efficiency compared with a DAB converter, although a filter capacitance is needed.

Power conversion is inevitable for MEA applications, since there are different voltage levels as mentioned previously. In [53], a quantitative method was proposed for comparing and designing multilevel topologies for large conversion ratio applications. In this study, the applications of flying capacitor multilevel converters (FCMC) and hybrid switched-capacitor converters in DC-DC conversion with a large voltage conversion ratio were explored. According to theoretical analysis and hardware test, it was shown that higher efficiency and power density are derived for these multilevel converters than conventional buck ones. However, the loss model was not accurate, and the volumes of active devices and auxiliary circuits were neglected. Moreover, based on the conclusions obtained in [53], the authors proposed an analytical comparison methodology for these converters with respect to the fundamental utilization of the active and passive devices in [54]. The efficient use of flying capacitors was presented for the hybrid Dickson switched-capacitor converter, which is a suitable candidate for designs with a large number of levels. On top of that, in order to meet the start-up requirements for the applications with auxiliary power supplies, a start-up circuit that directly supplies power to the auxiliary power converter was presented in [55]. A 5-level FCMC was applied due to its compactness and high efficiency in power conversion. This approach was demonstrated to reduce the voltage overstress on the switches from 22.8% to 7%. However, the inrush current was limited, and the FCML input voltage and flying capacitor voltages were slowly ramped.

A decoupled power flow three-port triple active bridge (TAB) topology that targets at solving the problems of power coupling and nonlinearity was proposed in [56] for high-voltage direct current (HVDC) application in MEA. The power density is high, and a simple control strategy can be used. In [57], an isolated multiport power converter was proposed, which includes the function of a high-frequency transformer. The multiport power converter was analyzed by modeling it as a two-input two-output system. Good performance during load changes and low DC voltage overshoots during transients were obtained, but singularity may appear for the compensation network at some operating points.

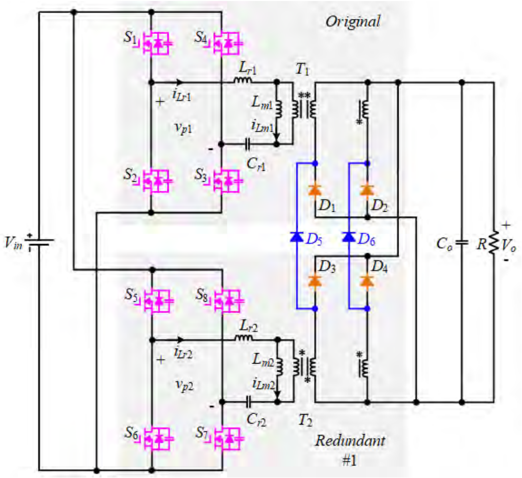

FIGURE 5. **The proposed fault-tolerant DC-DC converter in [58].**

The safe operation of MEA is critical, and the strict requirement of high reliability has to be met for the on-board power converters. In [58], the authors proposed a novel fault-tolerant LLC converter for MEA, which has two fault-tolerant capabilities on the short-circuit fault of switches by combining the advantages bridge reconfiguration and modular redundancy. Instead of using two redundant circuits, the authors in [58] proposed a fault-tolerant DC-DC converter that employs two diodes to replace one of the redundant circuit. A simplified circuit design and unified control system are the two major merits of the proposed fault-tolerant converter architecture, which is an excellent candidate to ride through short circuit faults for mission critical applications such as MEA. The topology of the proposed fault-tolerant DC-DC converter is displayed in Figure 5.

C. CONTROL TECHNIQUES

MEA is one of the typical applications with a wide output voltage range, which has a tradeoff with the power conversion efficiency. With the purpose of addressing this dilemma, a family of two-phase interleaved *LLC* (iLLC) resonant converters was proposed with a novel voltage regulation method with hybrid rectifier and variable-frequency plus phase-shift control in [59]. The proposed control method enables the converter to always operate in the region with the switching frequency lower than the resonant frequency. It was verified that ZVS of primary-side switches and zero current switching (ZCS) of secondary-side rectifying diodes can be obtained.

However, there are large voltage ripples during transitions. Moreover, the authors from the same group derived a novel three-phase three-port rectifier (TPTPR) as the PFC converter from the well-known three-phase six-switch boost rectifier in [60]. In order to reduce the conversion stages and improve the power conversion efficiency, a modified space vector PWM (SVPWM) strategy was proposed. The proposed strategy enables the direct feeding of AC input power to the low-voltage DC load within single power conversion stage. In addition, with the reduced switching losses, the power conversion efficiency of TPTPR is increased. However, additional bi-directional switches and capacitors, and SVPWM strategy complexity are inevitable. Furthermore, an integrated control strategy was presented in [61] to achieve fast start-up and wide input frequency operation in a three-phase six-switch PFC converter.

A quadruple active bridge (QAB) DC-DC converter is a good candidate for high step-up ratio applications, which realizes the series/parallel structures based on single-input single-output DC-DC converters with high-frequency transformers. In [62], a modular DC-DC converter with multiple QAB building blocks was proposed, which is endowed with the capability of routing the power through multiple paths. A lifetime-based power routing strategy based on virtual resistor voltage control was proposed to shift the thermal stress to the healthier part of the converter to extend its overall lifetime. The power rerouting can be achieved internally in fault conditions, but a lower voltage and an IR camera need to be used. Additionally, a QAB converter was used in [63] to interface a fuel cell (FC), a battery and a supercapacitor (SC) bank to the DC bus of the EPDS of an MEA. A novel decoupling control plus a feedforward action were proposed to shape the power flow request to each port.

D. POWER QUALITY

In [64], the power flow control, load priority shift, storage system performance optimization, and disturbance rejection improvement were investigated to improve the MEA system efficiency from the aspect of applying topological solutions with a mix of local and central controls taken into consideration. It points out that the optimal multi-objective management of the microgrid (MG) and the optimal subdivision of control tasks between local and central controllers are still the open issues.

As a powerful tool for compensating current harmonics and improving power quality for electrical systems, an active power filter (APF) is commonly used. In [65], an aeronautical APF (AAPF) with a two H-bridge cascaded inverter that works in a close-loop way was proposed for MEA EPDS. A feedforward path of the load current was added for the source current direct control-based AAPF to improve the dynamic performance of the load response. Good compensation behavior is obtained for various nonlinear load conditions, as well as excellent dynamic performance. While an additional capacitor is used, and obvious DC-link current ripples are presented. Since harmonic cancellation and power factor correction are two critical requirements for improving the power quality of MEA, [66] applied full-bridge inversion topology-based APFs along with harmonic-oriented control techniques for THD attenuation. Different from [66], a novel dual-buck inversion topology for APF was proposed in [67] to eliminate harmonics, correct the power factor of supplies, and minimize the effect of unbalanced loads. It was demonstrated that the THD and power factor of the generator voltage and current of the studied MEA power system with the proposed APF are in compliance with the most recent military aircraft electrical standard MIL-STD-704F. However, the proposed APF needs to be connected closely to the main generator to obtain these advantages.

In [68], a modified one cycle control (OCC) strategy was proposed for APF to compensate only harmonic components of load currents. This modified OCC overcomes the intrinsic disability of distinguishing harmonic components from reactive components of load currents for the existing OCC scheme. Compared to the harmonic compensation strategy in [69] that needs six more sensors, only three more sensors are required in [68] to retain the advantages of the existing method. However, a high switching frequency is still required. Additionally, as an efficient approach to mitigating harmonic pollution in the power networks of MEA, an active shunt filter (ASF) based on modular multilevel converter (MMC) configuration was proposed in [70]. It was validated that the current harmonic replica of the non-multiple 3rd order components are compensated and predicted by using the proposed control strategy.

Although the implementation of filters is powerful for assisting the MEA electrical power networks in fulfilling the current harmonic distortion regulations, the demerits such as weight and volume increases are presented. For the sake of not using filters in achieving the desired low individual harmonic current levels, a forced communicated controlled series capacitor rectifier (FCSC-rectifier) was proposed in [71] to maintain a high power factor and acceptable current harmonic levels in the case of large voltage and frequency variations. The effective capacitive reactance is to be matched with the generator inductive reactance, so that the above mentioned targets can be achieved without the need for additional filtering. While it is designed only for standalone applications, and the full range of output voltage fluctuations and frequency variation have to be handled. Moreover, the performance of FCSC-rectifier with a variable DC on-board load was analyzed in [72]. The steady-state behavior of FCSC-rectifier circuit was analyzed analytically, and the principle modes of operation of the circuit were described. Almost sinusoidal AC current waveforms are derived in a wide generator operating voltage and frequency ranges, along with an almost unity power factor. However, the application is limited to the circuits with high series inductance generators/sources.

A Discrete Fourier Transformation (DFT) based phase-locked loop (PLL) algorithm for estimating the fundamental phase and frequency in aircraft electrical systems was proposed in [73]. Better dynamic performance and reduced sensitivity to harmonics, noise and signal amplitude variations are presented, and the computational burden is limited by adopting short signal windows. However, the direct derivation of phase information by electrical measurement and operation is susceptible to disturbances, and it has poor frequency adaptive capabilities. Moreover, with the target of improving the quality of the phase and frequency real-time estimations, a robust PLL algorithm was presented in [74]. A third-order linear and time-invariant observation model was derived from a steady-state linear Kalman filter (SSLKF), which was experimentally compared with the technique proposed in [73]. Superior performance of the proposed SSLKF-PLL technique over the DFT-PLL one was verified in terms of the possibility of increasing the closed-loop control system bandwidth and significantly lower computational effort. However, the proposed SSLKF-PLL technique has larger maximum overshoots and steady-state oscillations in both the transient and steady-state conditions, and it has longer delay time and a larger steady state error regarding the steady-state performance.

E. THERMAL ANALYSIS AND MANAGEMENT

It is important to ensure good performance for the on-board power electronic devices for an MEA that operates under different temperatures. Therefore, thermal analysis and management for these power electronic devices have to be carried out.

The power variability is mitigated by proposing a power electronic controlled environmental control system (ECS) as dynamic thermal storage in [75]. The ECS was regarded as a heating, ventilation and air conditioning (HVAC) system in a ''flying building''. Relatively constant generator power consumption and a robust on-board power system can be derived, although limited application scenarios and large deviations in the temperatures are presented. In addition, a modeled electrical-thermal system was tested by a five-hour flight profile with the electrical load magnitudes based on Boeing 787 total electrical loading variations in [76]. The proposed virtual synchronous control method for thermal storage integration was incorporated with the Boeing 787 model.

The paralleled SiC MOSFETs rated at 1200V and 60A in [77] are required to operate in harsh environments of up to 200°C for MEA applications. The DC bus voltage and switching frequency were increased to 560V and 100kHz respectively to create the harsh environment with surface temperatures of over 190°C and around 200°C respectively for the top MOSFETs and middle device. There was no shoot-through and thermal runaway during the test, verifying good performances of SiC MOSFET at high temperatures. For the LCL filter design of a 50kW 60kHz SiC inverter in [46] for aerospace applications, a liquid cooling system of the amorphous cored inductor was described to handle the harsh ambient temperature environment. Besides, the inductor's thermal circuit model was shown, where the core loss contributed the most to the temperature rise. While the drawbacks are high inverter current harmonics and the inevitable installation of a liquid cooling system.

F. SUMMARY

SiC [44], [45] and GaN [46]–[49] are the promising materials for on-board power electronics to increase the switching speed and reduce the power loss. In terms of the architecture, PFC [50], [51], FCMC [53]–[55], and multi-port [56], [57] converters obtained much attention. Besides, the proposed control techniques aim to achieve the highest conversion efficiency when keeping a wide output voltage range. Moreover, appropriate design and control of APFs [65]–[67], [70] are significant for improving the overall power quality. All the advanced power electronics techniques reviewed for MEA applications are summarized with their themes, pros and cons illustrated in Table 4.

IV. ENERGY MANAGEMENT

Energy management plays a crucial role in the operation of MEA under different working modes. With the more-electric power distribution architecture, more flexible on-board power regulation is realized for MEA compared with the conventional ones. In order to take full advantage of this kind of EPDS, a number of research activities focus on the energy management for MEA EPDS with respect to energy storage systems (ESS), power distribution, and performance optimization.

A. ESS

As the electric power requirement for MEA is high, ESSs need to be integrated in this architecture to complement the power generation by usual generators. The electrical ESSs also play an important role in improving the reliability, stability and quality of the aerospace electrical networks. The energy storage devices for automotive applications like MEA can be generally divided into three types, which are batteries, super/ultra-capacitors, and FCs.

In [80], a high energy density Lithium Ion (Li-ion) ''Li-ion phosphate'' battery was selected and designed according to the requirements of MEA. The design and modeling of the battery system was presented based on a modified Shepheard curve-fitting model, with the modeling of DAB converter investigated with the consideration of the harmonic up to first 7 levels. The highest accuracy can be achieved with the harmonic number ''h'' = 7 selected. In addition, the same research team proposed a predicted peak current-based fast response control technique to integrate the battery ESS (BESS) with an MEA power system architecture in [81]. With the purpose of obtaining fast transient response, a maximum limit on the coupled inductor current was provided in the proposed control structure for the predicted peak current value. It was found that the DC offset current was derived as zero by applying the proposed control technique. However, the peak current has to be limited to a predefined value.

Owing to the complementary properties of SCs and batteries, a hybrid ESS (HESS) is usually applied for MEA to

TABLE 4. **Power electronics techniques for MEA.**

Research Field	Reference	Theme	Merits	Demerits
Material	[44]	1.2kV SiC MOSFETs for three-phase buck-type PWM rectifier	1. Much higher switching frequency 2. Significant reduction in converter weight and size	1. High cost 2. Not mature 3. At experiment stage
	[45]	Demonstration of a 50kVA 2-level 3-phase SiC inverter	1. Increased torque 2. Improved fault tolerance to phase open and short circuit fault conditions	1. Large weight for DC-link
	[46]	Comprehensive design flow of the LCL filter for a 50kW, 60kHz two-level SiC inverter	1. Systematic evaluation of the tradeoff among air gap, inductor weight, and thermal issue 2. Meeting the thermal requirement at full-load 50kW power	1. High inverter current harmonics 2. A liquid cooling system has to be used
	[47]	Demonstration of a 50kW SiC two-level three-phase VSI prototype	1. Switching frequency up to 100kHz 2. Narrow dead band of 250ns 3. Significant power loss reduction	1. No obvious increase in efficiency 2. GAC being less effective at low load current
	[48]	A three-level GaN DC-DC converter as a battery charger	1. ZVS in both operation modes 2. High power density 3. Minimized magnetic component sizes	1. Deteriorated performance at high switching frequencies in buck mode 2. Lower efficiency in LLC mode in full-load condition
	[49]	A GaN-based Vienna-type rectifier with SiC diodes	1. No instantaneous current information and pulse cycle adjustment needed 2. Convenient anticipation of voltage and current distortions	1. Limited harmonic rejection capability for 800Hz AC system 2. Visible certain 2^{nd} order harmonic
Architecture	[50, 51]	A three-phase buck-boost derived PFC converter	1. Elimination of current sensors 2. Only one voltage sensor needed	1. Lower control performance 2. The output filter is assumed to be large enough to keep the output voltage constant
	[52]	ABAC converter for interfacing a 270V DC network with a 28V one	1. Reduced converter weight and volume at high power ratings 2. LV current control with similar efficiency of a DAB converter	1. A filter capacitance is needed for current ripple suppression
	[53]	A quantitative method for multilevel converter evaluation and design	1. Keep the converter losses the same 2. Reduced passive component volumes 3. Higher efficiency and power density	1. Sacrificed result accuracy 2. Inaccurate loss model 3. The volume of active devices and auxiliary circuits neglected
	[54]	A general method for analysing resonant and soft-charging operation of switched-capacitor converters	1. Soft-charging operation 2. Resonant operation	1. An additional inductor needed
	[55]	A 5-level FCMC with integrated auxiliary power supply and start-up	1. Simple proportional control with a single capacitor voltage measurement 2. Reduced voltage overstress	1. Inrush current limited 2. Slowly ramped the FCML input voltage and flying capacitor voltages
	[56]	Decoupled TAB converter with energy storage for HVDC power system of MEA	1. High power density 2. Simple control strategy	1. Only applicable for full load scenario 2. Not mathematically accurate
	[57]	Power flow management of isolated multiport converter for MEA	1. Good performance during load changes 2. Low DC voltage overshoots during transients	1. Singularity free not guaranteed for the compensation network at all operating points
	[58]	A topology-reconfigurable fault-tolerant LLC converter for MEA	1. Significantly enhanced reliability 2. Low additional cost	1. Ideal short-circuit faults assumed 2. A redundant circuit
Control Techniques	[59]	A family of two-phase iLLC resonant converters with hybrid rectifiers	1. Variable frequency control 2. Phase-shift control 3. Low power losses	1. Large voltage ripples during transitions
	[60]	A modified SVPWM strategy for TPTPR with single power conversion stage	1. Wide voltage range 2. High power conversion efficiency	1. Additional bi-directional switches and capacitors 2. Complex SVPWM strategy
	[61]	An integrated control strategy for a three-phase six-switch PFC converter	1. Greatly reduced start-up time and inrush current 2. Fast and accurate tracking of phase current reference	1. High start-up phase current
	[62]	Lifetime-based power routing of a QAB DC/DC converter	1. Internal power rerouting in fault conditions 2. Maximized lifetime	1. Have to operate at lower voltage 2. An IR camera needed
	[63]	Use of a QAB converter for storage integration on the MEA	1. Galvanic isolation 2. Prioritized energy consumption 3. Power flow control at any controller bandwidth	1. High cost 2. No advantage by keeping the symmetry of inductances

TABLE 4. ***(Continued.)*** **Power electronics techniques for MEA.**

Power Quality	[64]	Improving the system efficiency for MEA	1. WBG devices offer higher conversion efficiencies 2. Reconfigurable architectures	1. Increased control and design complexity 2. Difficult optimal subdivision of control tasks
	[65]	Control and performance of a cascaded shunt AAPF	1. Good compensation behavior for various nonlinear load conditions 2. Excellent dynamic performance	1. Tradeoff between the power loss and reliability 2. deteriorated current tracking performance by "dead-time effect"
	[66]	Four hundred Hertz shunt APF for aircraft power grids	1. Eliminated shoot-through phenomenon 2. Improved compensation performance	1. An additional capacitor used 2. Obvious DC-link current ripple
	[67]	Design of APF for harmonics attenuation and power factor correction of an MEA power grid	1. Low voltage and current THDs 2. High power factor 3. Imbalances effectively handled	1. Need to be closely connected to the main generator
	[68]	A modified OCC-based APF for load current harmonic compensation	1. Easy to implement 2. No specially designed current controllers required 3. Reduced number of additional sensors	1. High switching frequency 2. Additional sensors required
	[70]	Power quality characteristics of a three-phase multilevel ASF with optimal predictive scheme	1. Compensate a wide frequency range of current harmonics 2. Modularity and redundancy functionalities 3. Capacity to ride-through parameter uncertainty and harmonic voltage drop at the PCC	1. Complicated algorithm 2. High THDs for the load currents
	[71]	FCSC-rectifier for MEA	1. High power factor over a wide range of voltage and frequency values at different load conditions	1. Limited to stand-alone applications 2. Need to deal with the full range of output voltage fluctuation and frequency variation
	[72]	Performance analysis of FCSC rectifier for MEA	1. Near sinusoidal AC current waveform in phase with the generator voltage over a wide range of operational voltages and frequencies 2. High power factor	1. Limited to circuits with high series inductance generators/sources
	[78]	A novel DFT-based real-time detection method for fundamental frequency and harmonic components	1. Fairly suitable for swift and accurate detection of the compensating current of ASFs	1. Compromise between the spectral resolution and computational effort 2. Update of vector cannot be implemented in the current step
	[73]	A DFT-based PLL algorithm for estimating the fundamental phase and frequency	1. Limited computational burden by adopting short signal windows	1. The direct derivation of phase information is susceptible to disturbances 2. Poor frequency adaptive capabilities
	[74]	A robust PLL algorithm for improving the quality of the phase and frequency real-time estimations	1. Possibility of increasing the closed-loop control system bandwidth 2. Significantly lower computational effort	1. larger maximum overshoots and steady-state oscillations in both the transient and steady-state conditions 2. longer delay time and larger steady state error regarding the steady-state performance
Thermal Analysis and Management	[79]	Cryogenic power conversion systems	1. Reduced fuel consumption 2. Make it possible to manufacture a superconducting generator unit	1. High system cost 2. Difficult to select and integrate the right cryogenic system
	[75]	Dynamic thermal storage for power system variability mitigation	1. Relatively constant generator power consumption and a robust on-board power system	1. Limited to a specific scenario 2. Large deviations in temperature
	[77]	Design of a 1.2kV, 60A SiC MOSFET multichip phase-leg module	1. Applicable for high-temperature applications	1. Limited by gate oxide stability 2. Slower ramp rates in the profile
	[46]	Comprehensive design flow of the LCL filter for a 50kW, 60kHz two-level SiC inverter	1. Systematic evaluation of the tradeoff among air gap, inductor weight, and thermal issue 2. Meeting the thermal requirement at full-load 50KW power	1. High inverter current harmonics 2. A liquid cooling system has to be used

achieve both good steady-state and transient performances. In [82], an HESS composed of SC and secondary battery was considered, and a sizing method was developed by taking their hybridization and characteristics into account to minimize the global storage system weight. A spider diagram was put forward to compare the characteristics of SC and Li-ion polymer battery, where an SC has higher specific power and a larger number of cycles, while a Li-ion polymer battery has a higher efficiency, longer discharge time, and stronger auto-discharge ability. Moreover, an optimal sizing tool was developed in [83] to set suitable parameters, including the cut-off frequency of the low-pass filter, the discharge ratio for storage components, and temperature. The study on the impact of setting parameters on the global storage system weight was carried out, and the EMS was adapted to preserve the battery. However, the battery performance degrades at low temperatures, and the effect of the added weight in the global optimization process was not taken into account.

A new real-time H_2-consumption-minimization EMS was presented in [84] for a fuel-cell hybrid emergency power system of an MEA. The proposed strategy is less sensitive to the load profile, and the design of cost function became simpler as the equivalent fuel consumption was ignored. Although superior fuel economy was achieved, high battery and SC stresses are inevitable. In [85], the authors proposed to validate the feasibility in using a modular PEM FC power system as the auxiliary power unit (APU) in an MEA with respect to a battery system installation from the specific energy point of view. A design method based on an optimization procedure with the size and efficiency of each power system component taken into account was applied to reach the maximum specific energy. An interesting value of the specific energy of the designed power system was found (0.51kWh/kg) by comparing it with that of commercial LiPo batteries (0.2kWh/kg). Moreover, a sizing and energy management strategy was proposed in [86] to determine the sizes of the hybrid source composed by a FC and battery pack.

B. POWER DISTRIBUTION

In [57], a power flow management strategy was proposed for an isolated multiport power converter to control the power flow among three HVDC electric networks in MEA. Three independent HVDC networks were arbitrarily chosen for investigation, and the combination of voltage droop and phase-shifted controllers was used to verify good power distribution performance under various load scenarios and partial or total generator fault conditions.

Different from the control strategies that receive power commands from a central control unit, a decentralized power management approach for EPDS in an MEA was proposed by generating the commands for power sources according to the data measured from the terminals in [87]. The desired power sharing ratio was to be obtained by effectively using the virtual impedance, and the appropriate designs of virtual resistance and virtual inductance respectively adjust the power sharing ratios at steady and transient states, which gives highly flexible configuration and power flow. However, obvious power difference is presented during the transient period. Besides, a modified mixed droop control method was proposed in [88] to realize decentralized energy management for a FC/SC-based APU of an MEA. The SC was applied to buffer all the pulsating or fast-changing loads, while the FC was responsible for supplying the average power demands. The optimized load power allocation can be achieved to not only extend the SC's lifetime, but also accommodate the regenerative energy in a lossless way. While the DC-bus voltage drop is to be eliminated by activating the line resistance compensation strategy, and the FC starts to supply some low-frequency components at certain cut-off frequencies.

C. PERFORMANCE OPTIMIZATION

In order to tackle the multiple objective optimization problem and fault mitigation issue in MEA, an energy efficient power management solution that focused on the design and implementation of power management system (PMS) was provided in [89] for a fault-tolerant MEA to optimize the EPDS level efficiency. A condition-based control (CBC) was integrated with the PMS to maintain the network resiliency and handle available resources at fault conditions. By predicting the power limits of generators, the constraints in PMS were updated with a stability tool. However, the responses of mechanical instruments are not fast enough, and the application of this strategy is limited to certain types of faults.

Aiming at achieving the optimal economic and environmental objectives for a hybrid electric unmanned aircraft (HEUA), the energy consumption and flight speed are coordinately scheduled to simultaneously minimize the fuel consumption and polluted gas emission (PGE). A multi-objective coordinated HEUA energy flight scheduling model was proposed in [90], which was formulated as a nonlinear multi-objective optimization model. In addition, a decomposition-based approach was developed to convert the original model into a bi-level programming one, where the two levels can be solved iteratively. By using the proposed coordinated energy flight scheduling strategy, a further 1.2% fuel consumption reduction and a 10% PGE reduction can be obtained compared with the conventional fixed flight scheduling. Nevertheless, one limitation of the proposed method is the ignorance of the stochastic disturbances experienced by the HEUA during flight.

D. SUMMARY

Batteries, SCs, and FCs are mainly used as ESSs for MEA, and HESSs are attracting more research efforts recently. Besides, decentralized and multiobjective EMSs are the main research trends for MEA EPDS. The summary of the research activities in energy management for MEA regarding ESS, power distribution and performance optimization is presented in Table 5.

V. SYSTEM STABILITY AND RELIABILITY

A high safety level of MEA is the most critical aspect to be considered, which is to be achieved by increasing the system stability and reliability.

A. SYSTEM STABILITY

Based on the Eigenvalue Theorem where the Jacobean matrix is utilized for the system eigenvalue calculation, the modeling and small-signal stability analysis were carried out for a hybrid EPDS in an aircraft AC frequency-wild power system in [91] that feeds a collection of AC and DC buses. The proposed modeling approach can be used to represent different on-board architectures in an algorithmic way, and it can predict EPDS instability due to operating point and system parameter variations conveniently. While it is only a general model, which is lack of accuracy for specific types of MEA.

Since a large number of power electronic loads are employed for MEA, and they usually behave as constant power loads (CPLs), a stability analysis of aircraft AC frequency-wild power systems with CPL was carried out by

TABLE 5. **Energy management studies for MEA.**

Research Field	Reference	Theme	Merits	Demerits
ESS	[80]	Modelling of a Li-ion BESS for MEA	1. High accuracy of power at “h” = 7	1. Limited to certain harmonic number
	[81]	Modelling and integration of a Li-ion BESS with the MEA 270V DC power distribution architecture	1. Better transient response 2. Zero DC offset current	1. Peak current limited to the predefined value of the inductor peak current
	[82]	Influence of energy management on sizing of HESS in MEA	1. dispatching of energetic requirements between both ESSs with initial sizing kept	1. Impossible to make the sizing results valid on the whole operating range
	[83]	Optimization of electrical ESS sizing for an accurate energy management in MEA	1. Minimized global storage system weight 2. The battery is preserved	1. Battery performance degraded at low temperatures 2. The effect of the added weight in the global optimization process not included
	[84]	A robust H_2-consumption-minimization-based EMS for a FC hybrid emergency power system of MEA	1. Less sensitive to the load profile 2. Minimized H_2 consumption 3. More efficient with superior fuel economy	1. High battery and SC stresses
	[85]	Design methodology for a PEM FC power system in MEA	1. Optimized energy/weight ratio 2. High specific energy	1. System level optimization not available
	[86]	Sizing and EMS of a hybrid FC/battery source for automotive applications	1. High gain for the hybrid source 2. Low current response time and power limits are respected	1. High cost
Power Distribution	[57]	Power flow management of isolated multiport converter for MEA	1. Good performance during load changes 2. Low DC voltage overshoots during transients	1. Singularity free not guaranteed for the compensation network at all operating points
	[87]	Decentralized power management for EPDS in MEA	1. Higher level of operational flexibility 2. Reliable and cost-effective management of MEA	1. Obvious power difference during the transient period
	[88]	A decentralized EMS for a FC/SC-based APU of MEA	1. Optimized load power allocation 2. Lossless energy regeneration 3. plug-and play function	1. The line resistance compensation strategy needs to be activated to eliminate DC bus voltage drop 2. FC starts to supply some low-frequency components at certain cut-off frequencies
Performance Optimization	[89]	An energy efficient power management solution for a fault-tolerant MEA	1. Improved system level efficiencies 2. Optimum efficiency achieved with fault tolerant network configuration	1. Responses of mechanical instruments may not be fast enough 2. Limited to certain types of faults
	[90]	Multiobjective coordinated scheduling of energy and flight for HEUA MGs	1. Further FC and PGE reduction 2. Avoid unnecessary charging/discharging cycles 3. Less time consumed	1. Contradiction between FC and PGE minimization 2. Ignorance of the stochastic disturbances during flight

employing the *dq* modeling approach in [92]. Lower order models were derived, and the modeling of vector-controlled converter elements is allowed. In addition, an adaptive backstepping controller was developed for a DC MG feeding uncertain loads in MEA in [93]. The desired DC bus voltage under slow and fast load power variations can be precisely tracked by using the proposed nonlinear control strategy. In [94], a module-based approach was proposed for stability analysis of complex MEA EPDS. The convenient formulation of a complex system model was achieved, and the proposed analytical model is effective in predicting unstable regions and investigating impacts of parameters. While the system stability cannot be guaranteed when large disturbances occur.

To complement the shortcomings of small-signal stability analysis, large-signal stability analysis is also carried out for optimizing the system design. In [95], the dynamic behavior of a hybrid AC-DC EPDS was analyzed in detail by considering large disturbances. The proposed method is computationally efficient for protection sizing and filter design optimization. However, the undervoltage protection need to be removed to ensure the predicted stability boundary is valid. Aiming at improving the stability of the AC cascaded system in an MEA, a large signal stability constraining dichotomy solution (SCDS)-based model predictive control (MPC) strategy was proposed in [96]. The Lyapunov stability criteria were included in the cost function. The large signal stability constraint can be derived in a clear way, and there is no need to consider how to select the weight of stability in the cost function, which is an advantage over the existing MPC methods. However, instability issues are caused by replacing the electrolytic DC bus capacitor with an LC EMI filter. Moreover, the stability analysis of a set of uncertain large-scale dynamical models with saturations was carried out in [97]. The associated errors of the reduced large-scale models are bounded. No parameterization is required, while the extension of the methodology to multi-input multi-output (MIMO) models is conditioned by the use of an interpolation technique with guaranteed error bounds.

In an MEA, DC MG architectures are commonly used over the past few decades since low total weight, high efficiency and low cost are derived. The modeling and small-signal stability analysis of a DC-distribution EPDS supplied by a PMSG were presented in [98]. A convenient and illustrative form of the effect of parameter variation on EPDS behavior, tendencies and direction of modal shift is presented, but the influence of cable has to be considered. On top of that, an improved voltage compensation approach was proposed in [99] for a droop-controlled MEA DC power system to effectively improve the load sharing accuracy with high droop gain by taking the cable impedance into account. Besides, the modeling and impedance analysis of a droop-controlled single DC bus based multi-source EPDS for MEA were investigated in [100]. A dynamic droop controller was proposed to provide active damping to the system. It was found that parallel sources can improve the system stability. With the increase of bandwidth, the performance is deteriorated. Moreover, the control design and voltage stability analysis of the same architecture were conducted in [101]. The proposed architecture has the potential to greatly reducing the EPDS weight, and the system stability is enhanced when the LP generator provides more power than the HP one. However, when the HP generator supplies more power, the system stability is deteriorated, especially at high power levels.

In order to reduce the volume and weight of the system without resulting in obvious instability of the DC microgrid by reducing the DC-bus capacitance, an observer was developed to estimate the load input voltages and remove the required voltage sensors in [102]. The instability issue was handled in a multi-load DC-power network, and three different types of loads were presented for a DC voltage source. Moreover, the concept of load identification and control was proposed for the DC EPDS of MEA in [103] to satisfy the large amount of power required without increasing the capacity of generators and energy storage, or implementing load shedding. However, it is difficult to model the higher order power dependency to voltage by using the proposed ZIP model, and the calculation accuracy of the load exponent is limited by the noise of the measured signals and the discretization of the analog-to-digital signals when a digital signal processor (DSP) is used. Furthermore, a practical method that uses the current perturbation was proposed in [104] to stabilize the on-board DC power converter system with an input filter. The oscillation is suppressed to improve the stability margin, and the size and weight are reduced. The original control structure does not need to change, while a sufficiently large band-pass filter has to be applied.

Small- [91]–[94], [98] and large-signal [95]–[97] stability analysis are commonly applied methods for evaluating the stability of MEA, and reducing the volume and weight of MEA by keeping high stability [102]–[104] is also a popular topic in academia. The summary of the research activities in system stability for MEA is given in Table 6.

B. SYSTEM RELIABILITY

In order to simplify the power electronics modeling process with accurate results and reduced simulation times for all types of system level studies, an alternative modeling approach was proposed for electrical fault analysis in [105]. Besides, the aircraft electric system intermittent arc fault detection and location based on transmission matrix modeling method was proposed in [106]. The normal and faulty load circuit models were derived with better accuracy and reduced complexity compared with the differential equation approach. In addition, high robustness of the proposed method is presented with the load switched on and off. However, high-frequency variations may occur when the load changes.

The electrical generators in MEA are usually driven by some form of mechanical drivetrains to supply power, while some disturbances occur between the electrical and mechanical domains. In order to identify electromechanical interaction at the design stage, an aircraft auxiliary power offtake was analyzed in [107] to produce a reduced-order mechanical drivetrain model. The resonances of the full system are characterized in both the frequency and time domains, and the verification of the reduced-order drivetrain model was implemented against both the full model and measured test data. While destabilizing results are inevitable as the interaction between the mechanical and electrical networks exists, and the torsional vibrations are presented. In [108], a hierarchical approach was proposed for systematic reliability modeling and evaluation for on-board EPDS of MEA. Three hierarchical levels, including the component level (HL1), subsystem level (HL2) and system level (HL3) are employed in the modeling and evaluation procedures. The hierarchical framework is very flexible and efficient in evaluating different system architectures. However, the considerations such as weight, volume, cost and efficiency need to be additionally combined with this approach.

The reliability of MEA EPDS is significantly affected by that of on-board drive system. In [109], a novel fault-tolerant drive system based on the redundancy bridge arm was proposed for aerospace applications. A dual-winding fault-tolerant motor was adopted, and a novel SVPWM fault-tolerant control strategy was proposed. The proposed fault-tolerant drive system can adapt to the single power supply system of MEA, reduce the drive cost, and cut down the number of independent power sources and switches. Meanwhile, the power density, reliability, utilization rate, and fault tolerance are increased. However, two additional switches are needed to control the connection between the motor windings and bridge arm midpoint, and complex programmable logic device control is required. Considering the failure mechanism of the power converters in MEA, a lifetime-based control method was proposed to optimize the system loading to delay the wear-out based failures in [110]. A reduction in the standard deviation of failures of about 44% was achieved, and three years of $B_{0.1}$ lifetime extension was obtained for the system, and the mean system lifetime was slightly increased. However, the proposed strategy is only applicable when all the thermal parameters are similar, and when the devices age equally.

TABLE 6. System stability studies for MEA.

Research Field	Reference	Theme	Merits	Demerits/Open Challenges
Small-Signal Stability Analysis	[91]	Modelling and small-signal stability analysis for a hybrid EPDS of MEA	1. Applicable for different on-board architectures 2. Predict EPDS instability conveniently	1. A general model without high accuracy for specific types of MEA
	[92]	A stability analysis of aircraft AC frequency-wild power systems with CPL	1. Lower order models 2. Allowing the modelling of vector-controlled converter elements	1. Limited to scenarios with the loads behaving as CPL
	[93]	An adaptive backstepping controller for a DC MG	1. Tracking the desired DC bus voltage under slow and fast load power variations	1. Limited to scenarios with the loads behaving as CPL
	[94]	A module-based approach for stability analysis of complex MEA EPDS	1. Convenient formulation of a complex system model 2. Effective in predicting unstable regions and investigating impacts of parameters	1. Cannot guarantee system stability when large disturbances occur
Large-Signal Stability Analysis	[95]	Dynamic behavior analysis of a hybrid AC-DC EPDS considering large disturbances	1. Computationally efficient for protection sizing and optimizing filter design	1. Undervoltage protection removed
	[96]	A large signal SCDS-based MPC strategy	1. Derivation of the large signal stability constraint in a clear way 2. no need to consider how to select the weight of stability in the cost function	1. Instability issues are caused by replacing the electrolytic DC bus capacitor with an LC EMI filter
	[97]	Stability analysis of a set of uncertain large-scale dynamical models with saturations	1. No parameterization required 2. Reduced and interpolated large-scale models	1. The extension to MIMO models conditioned by the use of an interpolation technique with guaranteed error bounds
Stability Analysis for MEA DC EPDS	[98]	Modelling and small-signal stability analysis of a DC-distribution EPDS supplied by a PMSG	1. Convenient and illustrative form of the effect of parameter variation on EPDS behavior, tendencies and direction of modal shift	1. Need to consider the influence of cable
	[99]	An improved voltage compensation approach for a droop-controlled MEA DC power system	1. Effectively improve the load sharing accuracy with high droop gain 2. Reduced DC transmission losses 3. System stability not deteriorated under both the normal and fault circumstances	1. High voltage regulation 2. Not applicable under certain situations 3. Obvious voltage and current ripples
	[100]	Modelling and impedance analysis of a droop-controlled single DC bus based multi-source EPDS for MEA	1. Improved system stability by parallel sources 2. Active damping provided	1. Poor performance in high bandwidth
	[101]	Control design and voltage stability analysis of a droop-controlled single DC bus based multi-source EPDS for MEA	1. Potential to greatly reducing the EPDS weight 2. Enhanced system stability with an appropriate power sharing ratio	1. Deteriorated system stability when the HP generator supplies more power
Volume and Weight Reduction	[102]	Active stabilization of DC MGs without remote sensors for MEA	1. A very large domain of attraction covering the validity domain of the DC MG 2. No dependence on the type of loads	1. The cutoff frequencies of the differential filters have to be much less than the switching frequencies of the converters
	[103]	Load control for the DC EPDS of MEA	1. Power requirement satisfied without increasing the capacity of generators and energy storage, or implementing load shedding	1. Difficult to model the higher order power dependency to voltage 2. Limited accuracy in the calculation of load exponent
	[104]	Stabilizing the on-board DC power converter system with input filter	1. Suppressed oscillation 2. Improved stability margin 3. Reduced size and weight 4. No change in the control structure	1. A sufficiently large band-pass filter is needed

The protection devices used in aircraft applications have also been widely investigated, and a survey of traditional and future trends of protection devices for aircraft electrical power distribution systems was carried out in [111]. The on-board protection devices used for all the EPDSs mentioned in [111] include the circuit breaker (CB), remote controlled CB (RCCB), arc fault CB (AFCB), and solid-state power controller (SSPC). Compared with CB, RCCB and AFCB, faster response, less weight and lower susceptibility are obtained for an SSPC. Thanks to the fast development of power semiconductor devices, SSPCs gain the highest popularity in the area of protection devices for aerospace EPDSs. A summary of the comparison among these four protection devices is displayed in Table 7.

In [112], the current state of interconnected generation in aviation industry and key technological advances that provide feasible interconnection options were discussed, and the interconnected systems can breach certification rules under fault conditions. In order to use light-weight and standards-compliant architectures, fast fault clearing protection is employed as a key enabling technology. Additionally, a novel smart fault current limiting CB (FCLCB) was

TABLE 7. **Comparison between the aircraft electrical protection devices reviewed in [111].**

	CB	AFCB	RCCB	SSPC
Remote Control	NO	NO	YES	YES
Arc Fault Protection	NO	YES	NO	YES
Type of Device	Mechanical	Mechanical	Mechanical	Electrical
Wiring Reduction	NO	NO	YES	YES
28 V_{dc} Applications	YES	NO	YES	YES
270 V_{dc} Applications	NO	NO	NO	YES

presented in [113] to reduce the fault current, open the faulty line, and improve the main bus voltage sag in the electrical distribution network for an MEA. However, the design of capacitor bank is difficult by considering the tradeoff between the on-state losses and total time constant. Moreover, a robust primary protection device was developed in [114] for a weight-optimized fuel system in the HVDC power system of MEA. A detailed description of the protection design process was included. The proposed novel protection device presents low complexity, light weight, and high robustness. It has a comparable mass to that of a standard CB or RCCB. However, perfect protection performance can only be achieved when the transistor with an extremely narrow current gain bandwidth is applied.

One of the obstacles that impedes the application of MEA is the thermal issue, which has to be taken into account to guarantee high system reliability. A survey on the present status of thermal load analysis and thermal management of the aircraft hydraulic system was conducted in [6]. Some considerations and thorough analysis on thermal management schemes and actuators in power by wire transmission

TABLE 8. **System reliability studies for MEA.**

Research Field	Reference	Theme	Merits	Demerits/Open Challenges
Fault Analysis Modelling	[105]	Simplified modelling process for electrical fault analysis of power electronics	1. Accelerated speed of simulations 2. High accuracy in the converter behavior 3. Allowing multi-resolution of a single network based model	1. Deteriorated simulation accuracy 2. A useful intermediate technique not available for multi-level model discretization
	[106]	Aircraft electric system intermittent arc fault detection and location	1. Better accuracy 2. Reduced complexity 3. High robustness	1. Occurrence of high-frequency variations when the load changes
	[107]	Analysis of electromechanical interaction in aircraft generator systems	1. A reduced-order mechanical drivetrain model derived 2. Full system resonances characterized in both the frequency and time domains	1. Destabilizing results
	[108]	A hierarchical approach for systematic reliability modelling and evaluation for on-board EPDS of MEA	1. Different operating conditions 2. Flexible and efficient	1. Considerations for weight, volume, cost and efficiency need to be additionally combined
Fault-Tolerant System	[109]	A novel fault-tolerant drive system based on the redundancy bridge arm	1. Adapt to the single power supply system of MEA 2. Reduced drive cost and number of independent power sources and switches 3. Increased power density, reliability, utilization rate, and fault tolerance	1. Two additional switches between the motor windings and bridge arm midpoint 2. Complex programmable logic device control
	[110]	A lifetime-based control method for system loading optimization	1. Around 44% reduction in the standard deviation of failures 2. Three years of $B_{0.1}$ system lifetime extension	1. Only applicable when all the thermal parameters are similar and the devices age equally
Protection Devices	[113]	A novel smart FCLCB for the electrical distribution network for an MEA	1. Changing the topology between normal and fault operation modes 2. Fault current breaking ability 3. Fast operation 4. Negligible switching overvoltage 5. Best system protection against the fault current	1. Difficult capacitor bank design
	[114]	A robust primary protection device for a weight-optimized fuel system in the HVDC power system of MEA	1. Low complexity 2. Lightweight 3. High robustness 4. Comparable mass to CB or RCCB	1. An extremely narrow current gain bandwidth to be chosen for the transistor
Thermal Management	[115]	Modelling of thermal phenomena in liquid cooling system for aircraft electric unit	1. The maximum temperatures of transistors and PCBs within the safety limits 2. Saved fuel metering pump dimensions 3. No additional components	1. Ignorance of the pumping power through the system
	[116]	High-performance EMA dynamic heat generation modelling	1. The temperatures within the motor of EMA all within a fairly narrow band 2. A complete picture of the dynamic behavior of EMA	1. Proper scaling has to be considered
	[117]	A hierarchical MPC approach for aircraft electro-thermal systems	1. Improved capability, safety and efficiency 2. Guaranteed constraint satisfaction in the presence of model and signal uncertainty	1. Poor flexibility 2. Communication barriers 3. Organizational disunity

system of MEA were presented. In [115], the modeling of thermal phenomena in liquid cooling system for aircraft electric unit was presented. A sufficient amount of heat can be effectively transferred out of the power and control electronic subsystem to keep the maximum temperatures of transistors and PCBs within the safety limits. The fuel metering pump dimensions are saved, and no additional components are required. However, the pumping power through the system was ignored. Since electromagnetic actuators (EMAs) are of special concern in the thermal management of MEA, a nonlinear, lumped-element, integrated modeling of a PM motor used in an EMA was established in [116]. A desired position profile, a load force profile, and an environmental temperature profile are taken as the inputs for this model. It was validated that the temperatures within the motor of EMA are all within a fairly narrow band, and a complete picture of the dynamic behavior of EMA is presented. While improper scaling may make the performance characteristic profiles of EMA deviate from the test one. Furthermore, a hierarchical MPC approach was developed for aircraft electro-thermal systems in [117]. The electrical and thermal systems are coordinated to decompose the multi-energy domain, constrained optimization problem into smaller, more computationally efficient problems to be solved in real time. Improved capability, safety and efficiency are presented, and the constraint satisfaction in the presence of model and signal uncertainty is guaranteed. However, the challenges of poor flexibility, communication barriers, and organizational disunity still exist.

In summary, the fault analysis modeling process varies for the device level and system level studies, and the electromechanical interaction analysis is attracting attention. In addition, the reliability of power electronics is a considerable factor in analyzing the MEA reliability. Moreover, the design of protection devices and implementation of thermal management strategies play key roles in affecting the system reliability. The system reliability studies for MEA are summarized in Table 8.

VI. CONCLUSION

A review of the electrical and electronic technologies used in MEA is carried out in this paper. With the emergence of MEA, most of the on-board nonelectrical subsystems are replaced by electrical ones. Meanwhile, the remote power distribution structure is presented for new MEA. The main research interests in MEA electrical and electronic technologies can be classified into the levels of powertrain and power system.

Electrical machines and power electronic devices are the two kinds of key power components at the powertrain level. At the power system level, the EMSs need to be appropriately designed to meet the specific requirements of MEA operation, and a number of studies focus on the system stability and reliability analysis. The detailed research directions and remarks are illustrated below.

1) For the researches on machine technologies in MEA, three categories of machines including IM, PMSM, and SRM were focused on. The main trend of research in this field aligns with enhancing the fault tolerance by proposing advanced machine design and control strategies. However, some degrees of compromise between the motor drive system performance and the system complexity/cost always exist, and most of the proposed methods are limited at certain operating modes and by system parameters. Besides, the applicability of these proposed methods is also related to the characteristics and operation of the corresponding power electronic drives. Therefore, improving MEA system performance by lowering the complexity and cost in the design and control methods for electrical machines and drives can be the research trend in the following few decades.

2) The investigations in MEA power electronics techniques are carried out in terms of material, architecture, control techniques, power quality, and thermal analysis and management. The WBG materials such as SiC and GaN are being investigated at the experimental stage. The power converter topologies of three-phase AC-DC converters, multi-level converters, and multi-port converters are within the scope of the main research fields in the power electronics architectures. Meanwhile, the modulation and control schemes of power electronic converters have been widely investigated. The open challenges are that almost all of the proposed methods have limited application scenarios. There is a huge research gap in the application of WBG power electronic devices in MEA, and there are many crossing fields to be investigated for the on-board power electronics techniques for MEA.

3) In terms of the EMSs for MEA, the modeling, design and implementation of ESS, power distribution and performance optimization strategies are reviewed in this article. The ESS sizing, aging and cost issues and the implementation of power distribution and performance optimization strategies are limited to certain operation conditions, and deteriorated performance may occur if these methods are not properly used. Therefore, more efforts are needed in the performance improvement in different operation conditions for MEA.

4) The research studies in system stability and reliability provide some guidelines in developing safer MEA through modeling, analysis and control for some of the crucial parts in the MEA EPDS, such as electric actuators and protection devices. The proposed strategies all have different degrees of limitations, and many of these strategies made some assumptions or ignored the influence from some on-board components. The others are conducted by comprehensively considering the system effects, while undesirable performances are presented. Therefore, more research contributions are required to expand the advanced approaches to a wider application field without severely deteriorating the overall system performance.

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