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Fault Management Strategies and Architecture Design for Turboelectric Distributed Propulsion

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Abstract— **The TeDP concept has been presented as a possible solution to reduce aircraft emissions despite the continuing trend for increased air traffic. However, much of the benefit of this concept hinges on the reliable transfer of electrical power from the generators to the electrical motor driven propulsors. Protection and fault management of the electrical transmission and distribution network is crucial to ensure flight safety and to maintain the integrity of the electrical components on board. Therefore a robust fault management strategy is required. With consideration of the aerospace-specific application, the fault management strategy must be efficient, of minimal weight and be capable of a quick response to off-nominal conditions. This paper investigates how the TeDP architecture designs are likely to be driven by the development of appropriate fault management strategies.**

Keywords—TeDP, architectures, redundancy, fault management

I. INTRODUCTION

The motivation to develop TeDP aircraft is driven by a desire to reduce aircraft noise, emissions and fuel burn [1]. An important aspect of the development of TeDP aircraft is that thrust is provided by propulsors powered by electrical motors [2]. Hence for the aircraft to maintain flight safely, a reliable supply of continuous power of an appropriate quality to the electrical motors is required. The electrical power network must be capable of distributing the electrical power from the generators to the motors during both normal and fault conditions.

Hence it is necessary for the system to be able to implement a fault management strategy when off-nominal scenarios occur. At a basic level, the fault management strategy underpinning all TeDP and conventional aircraft designs is mitigation against an engine-out failure scenario [3]. It is assumed that all fault management strategies for any chosen TeDP system will incorporate this essential capability and that the propulsors and other system components are sized accordingly [4].

However highly reliable, compact electrical networks require a wider view of fault management beyond engine failure [3]. Faults occurring downstream in the network also have to be considered since these too may contribute to a detrimental loss of thrust if the system does not respond appropriately. Thus the scope of fault management must consider the system as a whole. A pertinent challenge when considering the development of an appropriate fault management strategy is that the response of the system to a network fault is currently not fully understood [5]. In addition to the system response, the fault management system must also encapsulate system design, fault prevention, reconfiguration and condition monitoring.

In order to define optimal fault management more fully, this paper will first discuss a number of key objectives for fault management strategies. Secondly, a number of approaches to TeDP architecture design are identified in the literature. The resulting different approaches to fault management are discussed, highlighting the interdependency between fault management strategy and architecture. Finally, a selected case study is investigated in simulation, providing an insightful illustration of how architecture design is driven by fault management strategy.

II. IMPORTANCE OF FAULT MANAGEMENT STRATEGIES

A. Overview

In response to a fault scenario occurring on a TeDP electrical power system, the fault management strategy must ensure that the power delivered to the propulsors is above the minimum power demand at any specific moment in flight. This may include the appropriate isolation of faulted sections of network and re-routing of power to non-faulted sections. These fault management requirements put significant design constraints on the electrical architecture sizing and redundancy. The total weight of the electrical power system on a TeDP aircraft must not increase the fuel burn of the aircraft such that the potential efficiency benefits of the TeDP concept are lost. The choice of particular technologies, for example solid state circuit breakers, may be undesirable due to high cryogenic cooling requirements [6]. Similarly the impact of additional redundant cables or increased power rating of components on system weight and efficiency requires careful consideration.

Further fault management strategy challenges for future aircraft include:

- Protection equipment must fit within the airframe which constrains volume and placement of devices.
- Failures in cables and other electrical equipment must not cause failure of other components in the vicinity, especially fuel lines.

- The heat produced during a fault needs to be quickly and safely dissipated, to mitigate against propagation of quench (where the system is superconducting) [6]
- The desired protection technology may not be available at the required specification, for example at higher voltage levels (in the order of kV [7]) or able operate sufficiently fast (in the order of microseconds [8]).

B. *Key Success Criteria for Fault Management Strategies*

1) Early consideration in design process

In the first instance, potential fault management strategies for a particular network need to be identified and understood. It is then possible to scope the impact of each means of fault mitigation on the design of the network. Finally an optimal electrical power system design is selected, which can be adequately protected. Conversely, if protection is added as an afterthought to an established network design, an appropriate fault management system which can operate within system constraints may not be possible. For example, the weight penalty of the protection devices and redundancy may become inhibitive or lead to a solution which cannot provide the required levels of reliability. Alternatively, the necessary device specification may not be technically possible. This is summarized in Fig. 1.

It is anticipated that the fault management strategy may need to be adapted to accommodate other external factors, such as changes to the physical shape of the aircraft. The fault management system would then be reconsidered, leading to reconsideration of the network architecture, thus creating a cyclic design process.

2) Consideration of required speed of response

It is critical that the appropriate speed of response of the fault management system is identified. The architecture design will heavily influence this characteristic. For example if the electrical system on an aircraft includes converter interfaced sections of DC network with appropriate filters and low impedance cabling, then early studies have shown that unmanaged, low impedance faults will propagate quickly through the network [6]. The development of a fault management strategy with an appropriately fast response is extremely challenging. Different architectures may result in different speeds of fault propagation, which may result in fault management strategies which are more, or less, challenging.

3) Optimal reconfiguration

A fault management strategy must not only identify and locate a fault within a very short time frame. The fault must also be isolated and the power rerouted as appropriate before the reduction in the delivery of power to the propulsion motors becomes critical [4]. Hence the fault management system is more extensive than just the protection devices within the system: it must also be able to optimally reconfigure the available network as appropriate. This is highly dependent on the system architecture. For example, this may involve operation of bus ties, cable circuit breakers or joining of ring busbars. This aspect of fault management must consider all possible required changes to the nominal network and with an ultimate aim to ensure that the thrust remains symmetrically distributed (as possible) in the event that a fault should occur.

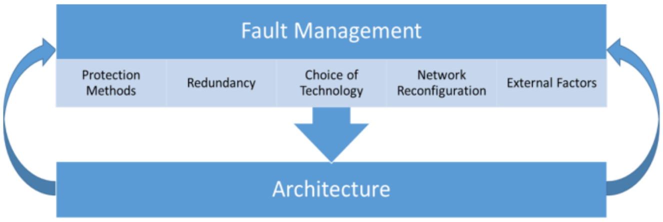

Fig. 1. Interdependency of Architecture and Fault Management

The method of isolating a faulty section of network will also strongly influence whether or not it can easily be recovered. If a section of the network is removed due to quench, then it is expected that the cable recovery time will be in the order of seconds to minutes [9]. This then has an implication on the system use as, depending on when exactly the fault occurs, it may not be feasible to bring the cable online again during flight. Thus the fault management strategy firstly has a significant impact on the flexibility of power flow, and secondly defines the way in which post-fault system recovery is controlled.

4) Targeted protection installation and operation

A further aim of the fault management strategy is to anticipate faults based on probability and severity, and implement a targeted response. It is not clear which type of fault effect (such as energy at the point of fault, instability or voltage droop) will have the greatest impact on the network architecture. The fault management strategy should ideally be robust and capable of mitigating against a variety of failure scenarios, and as a result is likely to require a tailored solution to address application-specific component sizing and expected failures.

C. *Interdepency of Fault Management and Architecture*

As discussed in Section II. B, the fault management strategy is a major driver for the TeDP electrical power system architecture design. To illustrate this further, the several aspects of fault management have been selected and their impact on corresponding architecture specifications discussed.

1) Quenching

It is suggested in the literature that a quenched cable may assist with limiting fault current [10]. If the effect of quenching is used in this way then there will need to be some means (e.g. a circuit breaker) in the system of isolating the quenched section. Alternatively, a redundant cable could be used as a replacement while the cable recovers. This approach may be attractive due to the expected significant weight penalty attributable to solid state circuit breakers due to their high on-state losses [6]. However, it must be considered that quench recovery may take a significant amount of time. In either case, a fault management strategy allowing areas to quench means that there will need to be a sufficient number of circuit breakers or parallel redundant cables installed. In addition there may need to be increased sizing of system components to allow the remaining network to compensate for the loss of power delivery.

2) Flexibility

If one aspect of the fault management strategy is to have flexibility in the power path between the power converters and the motors, (so that the network can be reconfigured after a section has been isolated) the architecture requires appropriate redundant cables, busbars and bus ties. The increase in system complexity provides significant challenges to develop an architecture with optimal performance in terms of weight and efficiency [3].

3) *Energy storage*

Energy storage has been proposed for more-electric aircraft applications both for fast network transients using high power density energy storage, and slower network transients, using high energy density energy storage [11], [12]. Therefore it would not be unreasonable to develop TeDP fault management strategy which includes the use of energy storage. However, whilst energy storage has been proposed for TeDP electrical power systems it is not yet clear what the exact role of the energy would be [4], [7], and whether this would change over the course of the flight [4]**.** The function of the energy storage during a fault would dictate not only the choice of energy storage, but its role during non-fault conditions and its location on the network. Hence it would influence the architecture design. Caution with the control of energy storage must also be taken, to ensure that energy storage does not increase the severity of a fault by discharging into a low impedance fault [13].

III. FAULT MANAGEMENT CASE STUDIES

A. *Overview*

In order to highlight the way in which a chosen fault management strategy can impact network architecture and the protection methods which would be appropriate, three fault management case studies from the published literature have been selected for discussion. The selected case studies reinforce that electrical system design for TeDP systems is strongly driven by fault management strategy. In all of the studied cases the electrical transmission and distribution network has been chosen to be DC. The reduction in losses [2] and reduced cabling [4] make medium voltage DC an attractive choice. The fault management strategies studied cover three possible cases:

- DC fault current can be interrupted, provided that the current is prevented from reaching its maximum by use of fault current limiters.
- DC fault current can be interrupted, but the weight of the circuit breakers will be large and so their use on the network is constrained.
- DC fault current cannot be interrupted, so the faulted network must be bypassed instead.Cross-Redundant Radial Architecture

The TeDP system in [4] (Fig. 2) is built on the assumption that it will not be possible or optimal to interrupt the maximum fault current in a medium voltage DC network. This is based on an assumption that the presence of high fault level sources like filter capacitors within a low resistance superconducting network will result in significant fault current peaks [5].

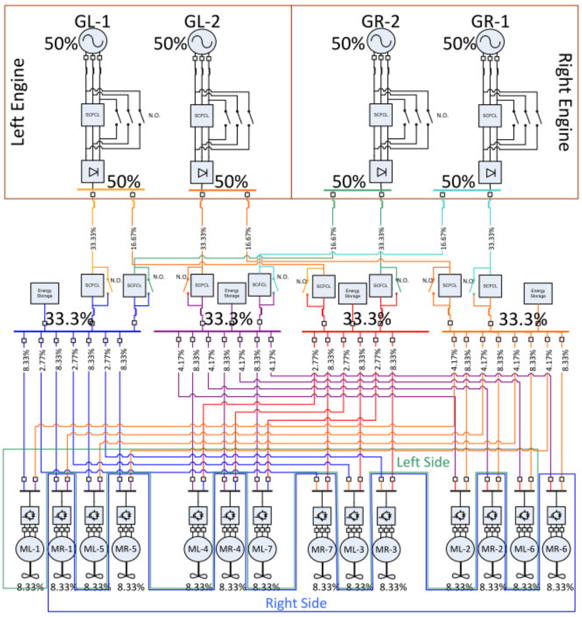

Fig. 2. Cross-Redundant Radial Architecture [4]

This fault management strategy operates with superconducting fault current limiters (SFCLs) be placed on all the sections of the network to restrict fault currents to below critical current levels. However, in order to isolate a faulted section of the network the inclusion of solid state circuit breakers (SSCBs) at the protection zone interfaces is required. Whilst initial studies have indicated that SFCLs have minimal impact on system performance, SSCBs do have significant detrimental impact on system performance (weight and efficiency) [6].

It is the choice of a radial architecture that has led to this fault management strategy. Furthermore, the feasibility of this design is sensitive to the future development of protection devices such as SFCLs and SSCBs. If, for example, due to physical airframe size or required electrical power system performance it would not be practical to have as many SFCLs or SSCBs on the network as shown in Fig. 2 then there would need to be a trade-off between the impact of an unrestrained fault current and the resulting increase in circuit breaker current rating that may then be required. This increased current rating would in turn further increase the weight penalty attributable to the protection system. Consideration should also be given as to whether expected fault current levels will be the main design driver for the electrical network, or whether other aspects, e.g. instability, thrust lapses or thermal system faults, will also have significant influence.

B. *Voltage Source Architecture with Fast Disconnects*

In contrast to the “Cross-Redundant Radial Architecture”, the design of the “Voltage Source Architecture with Fast Disconnects” [7] (Fig. 3) is based upon the assumption that it will be possible to interrupt the current but the number of circuit breakers which can be added to the network will be limited due to technological or weight constraints. Hence circuit breakers are only used at key selected points in the network: where the power converters interface with the distribution system, and at the AC terminals of the machines.

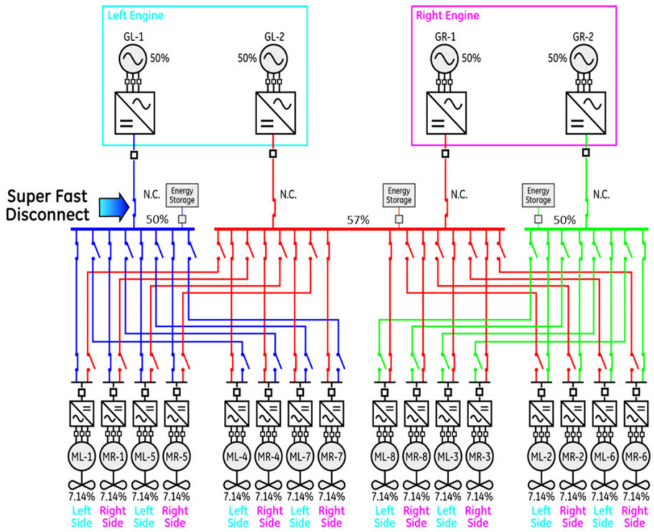

Fig. 3. Voltage Source Architecture with Fast Disconnects [7]

However, this architecture has been designed with "Super Fast Disconnects". These are used to reconfigure the 'dead' network to isolate the faulty section, only after all fault current producing elements have been disconnected by the circuit breakers. The circuit breakers are then reclosed to restore power to healthy sections of network. It is proposed that this allows for a significant overall weight saving as the superfast disconnects have a power density of circa 600 kW/kg compared to 200 kW/kg for the circuit breakers [7]. The superfast disconnects have an expected operating time of 1 ms [7]. The process of fault management may be more complex than the network in Fig. 2 because the disconnects must wait until the fault has been isolated since they have no current interruption capability. The communications required to operate the protection in this case require a sequential fault management process which must run successfully through each stage until the fault is cleared. This may increase the response time to a fault, which may be significant to maintaining appropriate levels of system performance.

Therefore, this architecture is dependent on an appropriately fast protection system response, the combined weight of the DC circuit breakers and disconnects, and the desired level of flexibility in the network reconfiguration. Hence it is evident that using disconnects with no current interruption ability as part of a fault management strategy has an impact on the placement of circuit breakers as well as the simplicity of the system response to a fault.

C. *Ring Architecture*

In the case that it is not possible to interrupt the DC current, then an alternative design proposal [7] (shown in Fig. 4) proposes shorting out (or bypassing) the faulted section of the network. This fault management approach requires a current source converter interfaced DC system, to enable a constant current to be maintained, including during system disturbances.

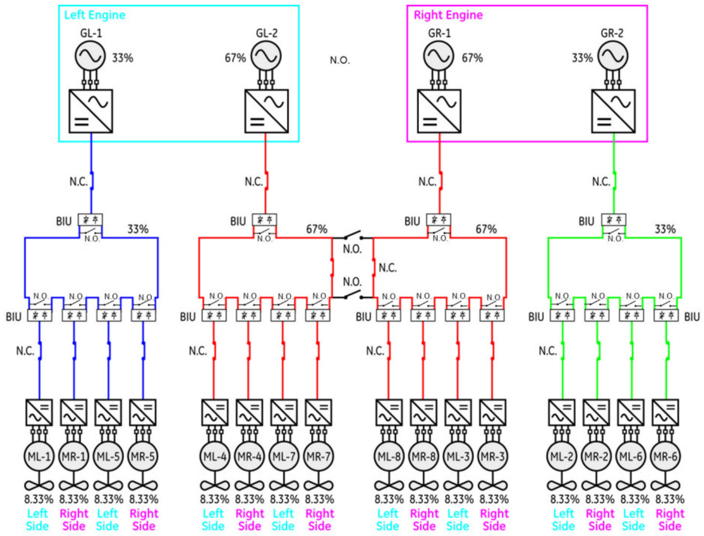

Fig. 4. Ring Architecture [7]

IV. INVESTIGATION OF EXAMPLE FAULT MANAGEMENT STRATEGY

A. *Overview*

To date, there are a limited number of published studies on the fault management approaches for TeDP systems and these have focused on the radial TeDP architecture [6][14]. However, the "Ring Architecture" has been selected for a detailed study as it presents a possible solution in the event that it is not technologically possible (or desirable due to performance constraints) to interrupt DC current in a DC TeDP transmission and distribution system. The system was modelled to investigate some of the key enabling factors for this architecture which are listed below:

- The system response when the switch operates to bypass the load.
- The impact of the speed of the response to the fault on the system voltage level.
- The impact on the remaining propulsion loads when one load quenches and is subsequently shorted out.

B. *Development of System Model*

A representation of a single ring busbar as described in Fig.4 was modelled as shown in Fig. 5. The power required by the loads on a single ring busbar was rated at 12.5 MW (half of the minimum 25 MW rolling take-off power available from a single engine) [3]. The total resistive load was taken to be 2 Ω, as defined by the power rating of the loads and the system voltage. Variable resistors are used to represent the superconducting cables. Values of cable inductance utilized are presented in Table 1. The ring busbar was set to operate within the possible voltage range of 1 to 10 kV [7]. The rate of quench (k_{quench}) used was 100 Ω/s, which is at the lower end of possible values for k_{quench} presented in [8]. This results in higher fault currents as the lack of resistance in the network leads to a reduction in available damping.

TABLE I. CABLE VALUES USED IN SIMULATION

	Line Inductance (μH/m)	**Length of Cable (m)**	**Inductance (μH)**
Load Cable	0.2[a]	5[a]	1
Busbar	0.2[a]	5[a]	1

[a] Based on values in [15]

[b] Based on estimates in [7]

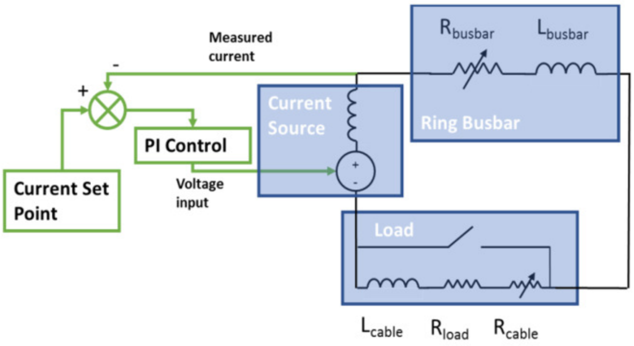

Fig. 5. Circuit Diagram

In Fig. 5, representing the upstream network, the behavior of the current controlled converter is approximated by a current controlled DC voltage source and series inductance representation. This is then connected in series with the loads. A bypass switch is placed in parallel with each of the loads to provide fault bypass/isolation capability. Since there are four propulsive motors on each ring busbar, the model contains four loads identical to that shown in Fig. 5. This then allows the effect of a single quenching incident on one load branch on the remaining loads to be assessed.

C. *Investigation of Fault Impact on System Voltage and Current*

During system operation, the current source should maintain a stable, constant output current. To achieve this, the terminal voltage across the source needs to adjust accordingly. At the point when quench occurs, the series current in the ring busbar decreases due to the increased resistance of the fault. This leads to an overshoot in source voltage in the time between the quench beginning and the bypass switch shorting out the faulted section of network.

After the system has reached steady state, each of the four propulsor load cables are set to quench sequentially (emulating fault effects), with the bypass switches effectively diverting the current flow from the affected branch after each fault. The bypass switch was set to close after 10 ms. This is much slower than quoted in [7] but was chosen in this case to show the system response clearly. The simulated source voltage during these events is shown in Fig. 6. The level of overshoot and change in impedance ratio of the quenched cable to the load is shown in Table II. The resistance of each fault after 10 ms is 1 Ω (representing a 100 Ω/s quench rate). The reduction in the system impedance as loads are shorted leads to higher voltage peaks during quench.

TABLE II. VOLTAGE OVERSHOOT FOR VARIOUS SIMULATED QUENCHES

		Overshoot Values			
Loads on Busbar Disconnected	**R_{quench} :R_{loads}**	**Peak Value (V)**	**Source Voltage (V)**	**Overshoot Amplitude (V)**	**Overshoot Amplitude (%)**
1	0.50	13517	10000	3517	35%
2	0.67	11056	7500	3556	47%
3	1.00	9211	5000	4211	84%
4	**R_{loads} = 0 Ω**	6461	2500	3961	158%

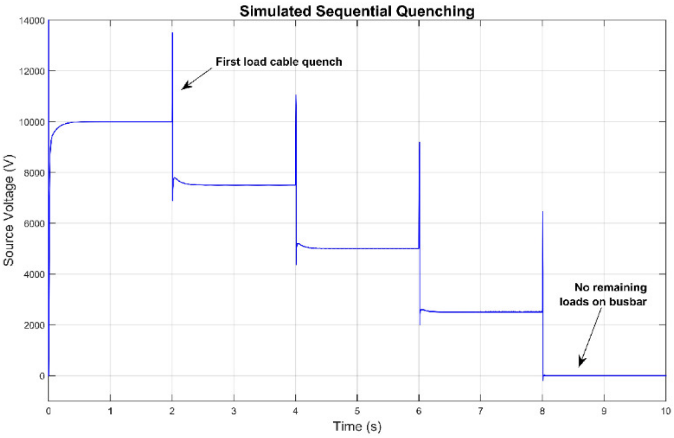

Fig. 6. Source Voltage Profile for Multiple Sequential Quenches

It is evident that the delay between the fault occurring and the operation of the switch bypassing the affected branch leads to potentially detrimental variations in current, reducing available thrust as less power is delivered to the motors. An additional concern is that current overshoots occurring immediately after the bypass switch operation may risk quenching of non-faulted cables. Therefore, the sensitivity of the system to changes in the time taken for the switch to operate was examined by simulating the model for a range of operating times operating at 5 kV, as shown in Fig. 7.

The results in Fig. 7 and Table III demonstrate that the operating time of the bypass switch is critical, particularly when the system impedance is low. The switching time of 1 ms (highlighted in bold in Table III) is the expected operating time of the bypass switch (this may be reduced to 0.1 ms if superconducting contactors are developed) [7]. The component specifications for this system (e.g. voltage tolerances) are clearly dependent on the response time of the fault management system, providing further indication that the fault management strategy must be developed prior to architecture system design.

The required closing time will depend on the component voltage tolerance ratings and the maximum increase in temperature that is acceptable during a quench. The availability, weight and volume of a switch able to operate in the appropriate kV range with a switching time in the order of ms will dictate whether this fault management strategy is in fact feasible in the future. These results show values for an operating point of

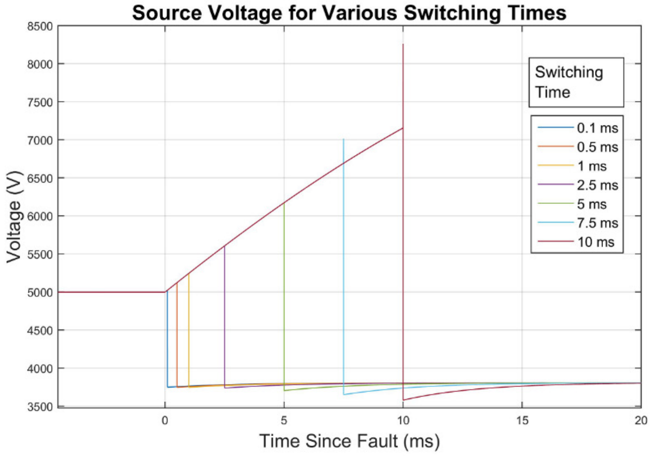

Fig. 7 Source Voltage Profile for Various Switching Times

TABLE III. OVERSHOOT DATA FOR VARIOUS SWITCHING TIMES

Operating Time of Switch (ms)	Peak Voltage Source Value (V)	Peak Overshoot (V)	Overshoot (%)
0.1	5022.82	22.82	0.45%
0.5	5122.17	122.17	2.39%
1	**5245.15**	**245.15**	**4.67%**
2.5	5607.96	607.96	10.84%
5	6173.00	1173.00	19.00%
7.5	7015.00	2015.00	28.72%
10	8262.00	3262.00	39.48%

5000 V, yet if the system voltage is specified closer to 10 kV or even higher, the voltage increase could be even more problematic for component voltage tolerances. This reinforces the importance of robust protection for cables and components with a rapid rate of quench and high reliability requirements.

V. CONCLUSIONS

It is clear that the fault management strategy will define the viable architectures for a TeDP electrical power system. A key driver for the fault management strategy is the operation of the electrical power system during off-nominal conditions. This impacts strongly on architecture choice and required network redundancy. The speed of response and the ability of the system to re-route power must be considered not only from the perspective of maintaining appropriate power to loads, but also to ensure system stability. The impact of system reconfiguration on the subsequent fault response of the system must also be given careful consideration. Furthermore, all of these specifications must be fulfilled within the stringent weight and volume constraints which apply to aircraft systems.

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