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Exploring Synoptic Display Concepts for Hybrid-Electric Airliner Flightdecks

Jeffrey H. H. Chen
Technische Universiteit Delft, Delft, Zuid-Holland, 2629HS, The Netherlands

Jonathan S. Litt
Glenn Research Center, Cleveland, Ohio

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Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Exploring Synoptic Display Concepts for Hybrid-Electric Airliner Flightdecks

Jeffrey H. H. Chen*
Technische Universiteit Delft
Delft, Zuid-Holland
2629HS, The Netherlands

Jonathan S. Litt
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio, 44135

The advent of hybrid-electric aircraft concepts with distributed propulsion has resulted in relatively complicated powertrain designs. Determining the optimal approach to display information about the hybrid system in the flightdeck has taken on great importance. At NASA Glenn Research Center, the concept SUbsonic Single Aft eNgine (SUSAN) hybrid airliner has been modeled inside a flight simulator where different flight deck displays can be evaluated. This work focused on ways to display information that reduce clutter and information overload without degrading the crew's ability to operate the aircraft and respond properly to emergencies. The displays' layout and symbologies were created to be intuitive to the pilots. This paper documents iterations of synoptic displays and discusses the rationale and tradeoffs behind each variation.

I. Nomenclature

AC	=	Alternating Current
DC	=	Direct Current
EE	=	Electric Engine
EEM	=	Electric Engine Motor
EICAS	=	Engine-Indicating and Crew Alerting System
EMR BAT	=	Emergency Battery
FAA	=	Federal Aviation Administration
GRC	=	Glenn Research Center
GTE	=	Gas Turbine Engine
HESD	=	Hybrid-Electric Synoptic Display
HPS	=	High Pressure Spool
LPS	=	Low Pressure Spool
MFD	=	Multifunctional Display
MG	=	Motor-Generator
NM	=	Nautical Mile
PFD	=	Primary Flight Display
SRG BAT	=	Surge Battery
SUSAN	=	SUbsonic Single Aft eNgine
TEEM	=	Turbine Electrified Energy Management
UI	=	User Interface

*NASA Intern for OSTEM internship program at Glenn Research Center

II. Introduction

Research on the conceptual SUbsonic Single Aft eNgine (SUSAN) airliner is being conducted across multiple NASA centers as part of NASA Aeronautics Research Mission Directorate's efforts to facilitate sustainable aviation [1]. SUSAN (Fig. 1) is a 737-sized hybrid-electric regional transport aircraft [2] that carries a maximum of 180 passengers, cruises nominally at Mach 0.785 at 37,000 ft, and can fly a maximum range of 2500 NM or an economic range of 750 NM [3, 4]. The overarching objectives are to reduce unit and operating cost without compromising safety [3] and to reduce emissions by meeting targets set by worldwide aviation authorities such as the International Air Transport Association's aspiration of halving net carbon emissions by 2050 relative to 2005 [5].

In order to realize these ambitious visions, SUSAN integrates a myriad of novel technologies expected to be fielded on hybrid airliners in the 2040 time frame [6]. In its current configuration, SUSAN is uniquely equipped with only a single dual-spool 21,000 lb_f Gas Turbine Engine (GTE) [6]. Continuing the historical trend of reducing the number of engines in order to increase efficiency and curtail maintenance cost, the single-engine design is motivated by the conviction that future transport configurations will employ only one or even no GTEs [3]. The GTE for SUSAN will generate around 35% of the total thrust [3, 4], is mounted in the aft fuselage for boundary layer ingestion and serves principally to power rows of underwing distributed and ducted electric propulsors, which have a combined rating of 20 MW [3] and provide the other 65% of thrust [6]. The aircraft also features other novel technologies such as new engine control strategies that allows the engine to be downsized [2, 7, 8], a natural laminar flow wing [9], superconducting motors [10], and the widespread incorporation of rechargeable batteries [6]. The latest variant SUSAN v3 is expected to offer a 26.8% reduction in fuel consumption relative to the Boeing 737-800 [4].

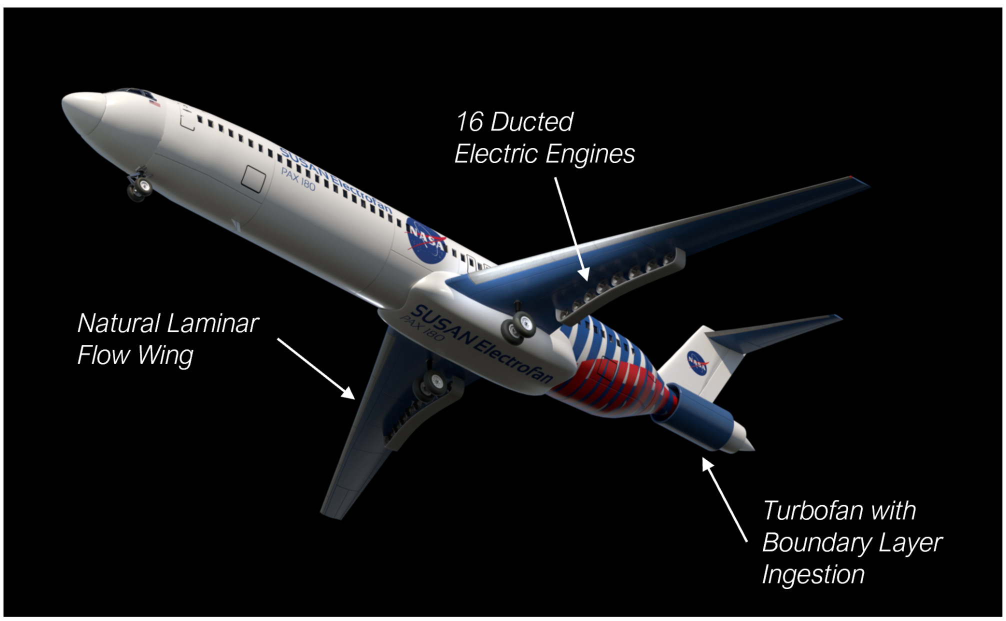

Fig. 1 3D render of SUSAN v3.

The objective of the SUSAN research is to develop the technologies necessary for hybrid aircraft of the future. Through the process of integrating technologies across multiple disciplines into an entire aircraft and modeling these new systems both in software and hardware, knowledge gaps that have been traditionally overlooked are inevitably revealed.

One uncharted area revealed by SUSAN's development is the challenge of designing glass flightdeck displays for hybrid airliners. As the industry focuses efforts on electrifying aviation, hybrid airliners are expected to become more prevalent in the coming decades, and already many conceptual designs have been studied or proposed by industry leaders and start-ups alike. For example, EasyJet is collaborating with Wright Electric to build the Wright 1 [11], a distributed-propulsion regional airliner based on the eMSTAR concept [12] targeting entry into service in 2030. Airbus and Safran have also converted a Daher TBM-900 turboprop into a hybrid distributed propulsion testbed by mounting six turbogenerator powered electric motors across the span of the wing [13]. Under NASA's Electrified Powertrain Flight Demonstration project, the agency has partnered with General Electric and Boeing to modify a Saab 340B into a hybrid-propulsion demonstrator [14]. Future hybrid aircraft will incorporate more extensive electrical systems compared to conventional airliners of today, especially if distributed propulsion is employed. The synoptic display, which presents the status and health of these complicated systems, must not only fit within limited screen space of traditional displays, but also be readily readable without increasing the workload of the flight crew. The core question thus lies in which information could be condensed, simplified, or wholly omitted without degrading the crew's situational awareness, workload, and ability to diagnose emergencies. While automation is expected to manage most of the hybrid system, the degree of manual control the crew is provided dictates what should be displayed. Generally, if the crew cannot act upon a certain piece of information to aviate safely or diagnose an emergency, then there is little value in displaying it. Limited research has been published regarding this question in the context of hybrid airliners, and as no hybrid airliner has yet to enter service, there exists no commercial design precedent.

At NASA, flightdeck displays for SUSAN are being investigated on two fronts. Firstly, studies are underway at Langley Research Center's Research Flight Deck to explore the optimal number of throttle levers to control SUSAN's 17 engines, and how to present engine information on the Engine-Indicating and Crew Alerting System (EICAS) [15]. Meanwhile, development has concentrated on synoptic pages for the Multifunctional Display (MFD) at Glenn Research Center (GRC), particularly one about the hybrid-electric system. It is this Hybrid-Electric Synoptic Display (HESD) that the paper covers.

At GRC, SUSAN has been implemented in a flight simulator, which provides a platform to both test aircraft handling and implement and experiment with different interfaces on its glass displays. Work initially concentrated on creating a MFD with switchable synoptic pages based on traditional systems that already exist in contemporary airliners, such as synoptic displays for the control surfaces, fuel system, and the landing gear. In addition to this work, SUSAN's unique architecture naturally required a synoptic display for its hybrid system. As hybrid aircraft become increasingly complex, delivering information in an uncluttered and comprehensible manner becomes ever more crucial. Thus, the principles which guided the conception of the HESD for SUSAN will apply beyond this particular aircraft.

III. SUSAN Hybrid Architecture

SUSAN's hybrid-electric powertrain is shown in Fig. 2. This section will summarize how the system functions and the rationale behind the layout which will allow a better understanding of what the synoptic display depicts and which aspects of the architecture have been simplified or omitted. The architecture is still a work-in-progress, so the layout may evolve in future variants of SUSAN. More details about each component can be found in [10].

A. Electric Engines

Approximately 65% of the aircraft's thrust is produced by 16 Electric Engines (EE) installed beneath the wings adjacent to each other in a mail-slot configuration [4]. Each EE consists of two contra-rotating High Efficiency Megawatt Motors (HEMM) and fixed-pitch fans housed in a single duct. The motors are superconducting and self-cooling [10], and are rated for a maximum of 0.8 MW but are downrated to 0.6 MW [3]. Each EE is powered by its own independent AC bus, resulting in 16 buses. Adhering to aviation convention, the EEs are numbered left to right from 1 to 17; engine 9 is reserved for the centerline turbofan engine.

B. Motor-Generators

A total of five motor-generators (MGs) are driven by the turbofan; four 5 MW MGs are attached to the low pressure spool (LPS) while one 1 MW MG is attached to the high pressure spool (HPS). Within each MG are four separate windings that are each independently connected to an individual EE. Therefore, each MG powers four EEs.

The LPS MGs produces most of the power for the EEs, while the main purpose of the HPS MG is to implement a control strategy called Turbine Electrified Energy Management (TEEM). In short, by regulating the power drawn from the MGs and adjusting the torque load on the engine spools, the rotational speed of both spools can be controlled electrically. During throttle transients, TEEM forces both spools to accelerate or decelerate in matched conditions, minimizing excursions from the compressor operating line. This potentially allows for a lighter engine by reducing the transient margin that must be built into the compressor[2, 7, 8, 10, 16].

C. Batteries

TEEM requires energy to be traded between the LPS and HPS, so a rechargeable surge battery is required to store and release energy from one spool to another. These surge batteries also boost throttle response. Each bus is connected

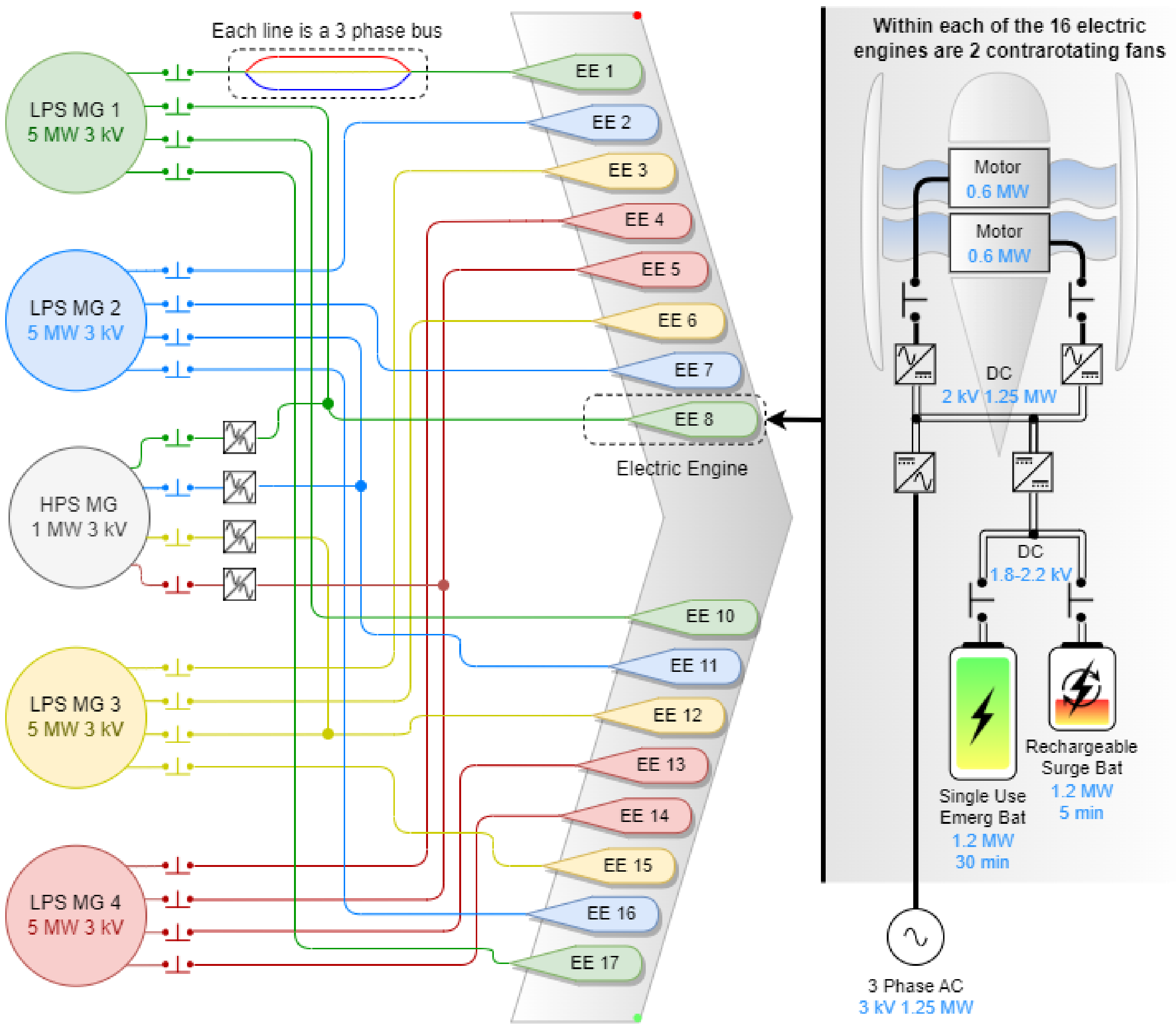

Fig. 2 SUSAN's hybrid architecture.

to a dedicated surge battery, although only four out of the 16 buses are connected to the HPS MG. The surge batteries also provide boost power during takeoff or climb [10]. During GTE engine start, the HPS MG acts as a starter motor powered by the surge batteries [17], which eliminates the weight penalty of carrying an auxiliary power unit.

Each bus is also connected to a single use emergency battery. In case of a GTE failure, the emergency batteries can provide 30 minutes of flight time allowing the aircraft to fly approximately 300 NM at Mach 0.785, sufficient to divert to a suitable airfield from almost anywhere within the United States [18].

D. Buses

There are 16 electrical buses all powered by the LPS MG. In Fig. 2, the buses are color-coded based on which LPS MG they are powered by. A bus from each color (four out of the 16 buses) is connected to the HPS MG to facilitate TEEM and engine start [17]. The AC portion of each bus is 3-phase. Circuit breakers can disconnect each bus from the MG, batteries, or motors to protect the components during a malfunction. It is expected that the breakers can be toggled both by the on-board automation and manually by the crew [19].

Having 16 independent buses mitigates the loss of thrust if a bus fails. The high level of redundancy also relieves the need for cross-ties that feed power from a working bus to an inactive one and downsizes the generators. The result of this symmetric fail design prevents an asymmetric thrust condition if a MG fails [2]. This particular distribution will present a challenge in the display of the propulsion system state to the flight crew.

E. Converters

The Motor Generators (MG) and Electric Engine Motors (EEM) are driven by AC current while the batteries must be connected to DC current. Converters convert between AC to DC (or vice versa) or act as controllers. Each DC/AC converter acts as the motor controller within the EE [2]. On the HPS MG there are four AC/AC converters that serve to control the HPS for TEEM and match the frequency with the AC power from the LPS MGs. The batteries are also controlled by a DC/DC converter.

IV. Flight Simulator Implementation

This section describes how the proposed displays were created and implemented in the simulator at GRC. The inherent limitations to the methodology are also discussed.

Fig. 3 The flight simulator setup at GRC. An earlier iteration of SUSAN's EICAS and HESD is shown.

A. Hardware

The flight simulator consists of an enclosed flight deck with instrument displays and flight controls for a pilot and copilot. Realism is enhanced by four motion actuators mounted to the flight deck base along with out-the-window scenery provided by five monitors affixed to the windows. The yokes and rudder pedals feature force-feedback. The two head down displays, as shown in Fig. 3, are 13.5 by 10.5 inches with a resolution of 1280 by 1024 pixels. The left head down display renders typical flying instruments such as the Primary Flight Display (PFD), a Horizontal Situation Indicator (HSI), and the EICAS, which contains engine information and warning messages. The right head down display is dedicated to the MFD, which hosts the switchable synoptic displays. The glass displays are not touch-sensitive and must be controlled with physical switches. While modern aircraft (notably the A220 [20] and the A350 [21]) feature wider head down displays than those in the simulator, each screen is typically divided between multiple pages of smaller aspect ratios in which these concept displays can fit.

B. Modeling

The flight simulation software X-Plane 11 was primarily used to provide out-the-window scenery of the flight simulator. While X-Plane features its own physics and systems models, these models are largely simplified and inadequate for the depth and complexity of SUSAN's development. X-Plane's internal physics is therefore overridden in real-time by a comprehensive Simulink model of SUSAN that employs NASA developed Simulink toolboxes to simulate the flight dynamics and the powertrain [6]. In regard to the flight deck display, the model can drive instruments that X-Plane does not natively support. More information about the Simulink model and the toolboxes involved can be found in Litt et al. [6].

C. Displays

Aside from rendering the exterior scenery, the instruments are also driven and animated by X-Plane. The project leveraged X-Plane's native support for users to implement their own custom aircraft with custom flight deck displays. The instrument panel was assembled in an auxiliary X-Plane software tool called Planemaker (Fig. 4).

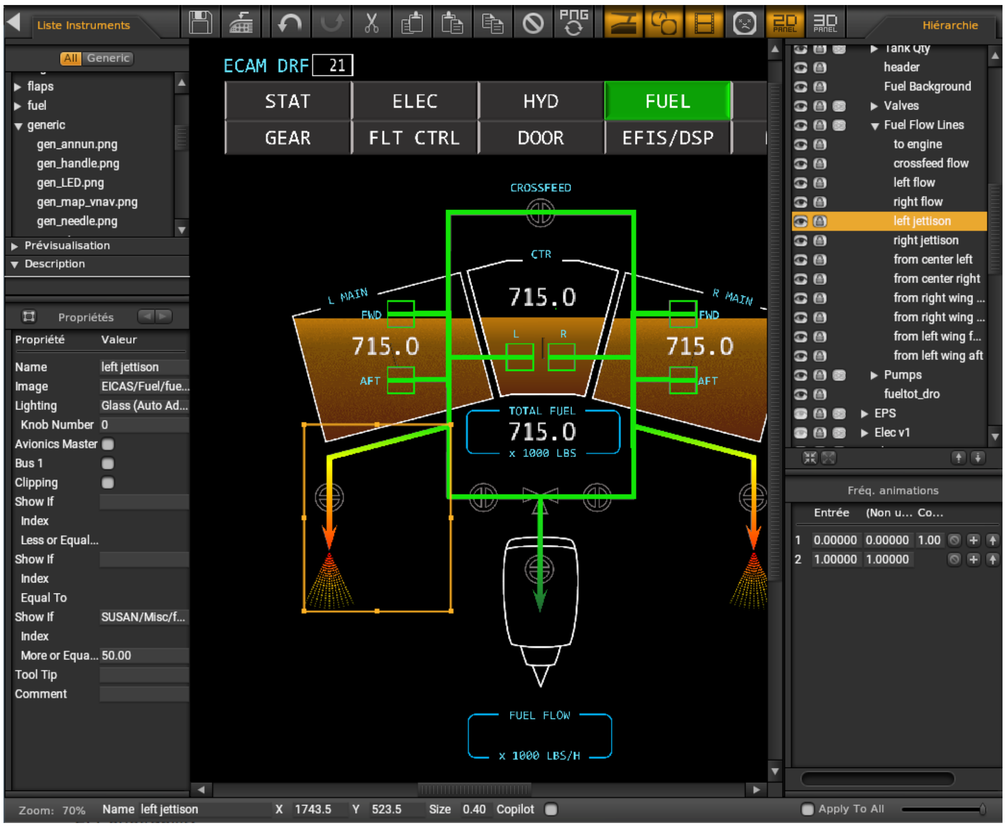

Fig. 4 A concept fuel synoptic page for SUSAN inside Planemaker's 2D panel builder.

The shapes and symbols were created in 2D editors such as Powerpoint and Gimp. These image elements were then imported into Planemaker, where their animation was defined and tied to an output data-reference variable from X-Plane [22] or SUSAN's custom simulink model. Since the physical simulator lacked a cursor or a touchscreen, a rocker switch on the yoke (a repurposed trim switch) allowed the pilot to cycle through engine synoptic pages.

D. Limitations

The glass displays proposed herein were designed with their implementation into the simulator as a priority. Therefore the graphics are limited by what X-Plane can animate. While SUSAN in general represents a 2040s design, the displays may not depict the most futuristic concepts proposed by the industry. The animations for custom instruments supported by X-Plane centers around replicating analog instruments, and the implementation of digital displays often involved workarounds. Symbols with complicated animations, digital checklists, or 3D visuals like synthetic terrain require additional plug-ins to implement, which lies outside the scope of the project. Despite these limitations, X-Plane's supported animations suffice for displays created with simplicity in mind. The focus of the work was to explore methods to convey the hybrid system in a familiar format, rather than to develop the most revolutionary flight deck displays.

V. Display Guidelines

The design of avionic displays draws from a diverse range of knowledge, such as safety engineering, User Interface (UI) design, human factors, and airmanship. Kathy Abbott, the FAA's Chief Scientific and Technical Advisor for Flight Deck Human Factors, writes:

> "The process by which commercial flight decks are designed is complex, largely unwritten, variable, and nonstandard...Historically, this process tends to be very reliant on the knowledge and experiences of individuals involved in each program."[23]

These levels of expertise in the wide breadth of fields involved in the formal and rigorous design of novel displays far exceeded the available resources of the project. In order to expedite implementation, many visual elements were not created from scratch but designed in the style of existing displays, particularly visual elements from Boeing and Airbus. The intention is not only to preserve a certain level of commonality, but also implicitly inherit some human-factors motivated design choices as a way to ensure pilot familiarity. In this manner, the project's time could be devoted to iterating on the display for SUSAN. Therefore, the concepts presented below still necessitate further infusion of knowledge from the aforementioned fields.

Nevertheless, the design of the displays was still informed by the following general guidelines:

1) **Intuitive –** The display should enable the pilots to find the information they seek rapidly and easily. There should be minimal sources of confusion, especially critical under high-stress, fatigue, or hypoxia, where cognitive abilities may be impaired. IBM recommends that a user-interface should build on the user's prior experience and act predictably [24]. Visual elements and color-coding should be intuitive, self-explanatory, or follow aviation convention. In other words, revolutionary solutions should only be employed where conventional methods are inadequate. UI design guidelines will be applied to increase intuitiveness.
2) **Organized –** The layout should be organized according to a clear logical rule [24, 25]. According to a guideline from the Society of Automotive Engineers, "Systems displays should present system information in a format that corresponds to relative positions in the aircraft of the system components." [26] The layout should also aid visual workflow. For instance, frequently sought information should be placed in close proximity to reduce glancing distance. Grouping or clustering should be leveraged to increase organization [27, 28]. These strategies reduce the time and cognitive workload needed to read the display.
3) **Distinct –** Indicators should be distinct and not easily confused with other symbologies. A single indicator should always represent the same information. The 1967 crash of a X-15 was partially caused by an attitude indicator that displayed either the angle of attack and sideslip or pitch and roll with the same pair of needles depending on setting. The poor design likely confused the pilot, who inadvertently maneuvered the aircraft into a spin at Mach 5 [29].
4) **Obvious –** Critical information and warnings, such as an engine fire indicator, should be obvious and difficult to ignore. In 1989, a British Midland Airways 737-400 suffered a left engine failure. The lack of a specific warning to indicate elevated engine vibration, along with the probable conflation between the left and right engine indicators, contributed to the crew shutting down the right working engine, ultimately leading to a fatal crash [30].
5) **User-friendly –** From a UI standpoint, text and symbols should be sized legibly and menus easily navigable. Clutter should be avoided with adequate spacing between indicators. Indicators should be labeled appropriately with legible text [31]. Low-contrast color combinations should be avoided [32, 33]. The displays should be readable under varying lighting conditions.
6) **Simple –** An avionic display should provide sufficient situational awareness while avoiding information overload. Hick's Law, a psychological principle, correlates amount of stimuli to reaction time (regardless of whether the information is relevant or not) [27, 34]. In other words, providing more information will increase the crew's cognitive load and the time required to make a decision [35, 36]. Therefore it is essential to scale the detail of information based on the degree of control provided to the crew over the system. Moreover, information should be visible only when it is relevant to a particular situation.
7) **Themed –** The displayed parameters must be anchored to a central theme or philosophy that enables the crew to easily conceptualize the system. Conceptualization entails not only acquiring the data but forming a mental model of how the system functions. When characterizing the status or health of a component, designers may need to choose from several available parameters. For instance, an electrical component could be characterized by voltage, amperage, or power. The chosen parameter(s) must be consistent across multiple components on the display, following a theme that enables quick conceptualization.
8) **Aesthetic –** While aesthetics is often overlooked in engineering applications, the glass display should still provide

a pleasant user experience [25]. In 1995, the Hitachi Design Center discovered that aesthetics impact user perception more so than underlying functionality [37]. Aesthetics can be leveraged to psychologically enhance the apparent usability of a display [27, 38]. While aesthetics is difficult to qualify, by adhering to contemporary graphic-design trends such as a visually minimalist theme, the visual presentation can be rendered agreeable and clear, further reducing cognitive load.

The FAA provides an extensive compilation of guidelines in [25]. Many of the guidelines above, particularly those regarding color and layout, were challenged, and the justifications will be discussed below.

VI. Hybrid-Electric Synoptic Display

The HESD is designed as a selectable page within the MFD. Therefore, it is not a primary flight display that is always in view like the EICAS, but instead offers a detailed overview of the hybrid system that the crew can use to monitor the system or diagnose failures. The HESD was envisioned to deliver similar information as the electrical synoptic display found on the MFD of conventional airliners, which typically shows the status of the batteries and buses.

This section chronicles the design process of the HESD, which progressed through two iterations before arriving at the final one. In each iteration, the justification behind the design choices and the various trade-offs will be discussed. Each iteration inherited elements of design from the previous. Various challenges and drawbacks that motivated each redesign are also described.

A. Iteration I: Four Page HESD

Initially, the plan was to display the entire electrical system on a single screen with 16 columns, each hosting dials and indicators for the components of each bus. This is a familiar organization akin to how engine information is traditionally displayed on multi-engine aircraft. However, due to the large number of buses, this arrangement forces each dial to be illegibly small. Therefore, in the first concept of the HESD, the electrical system is divided into four separate pages, each displaying four buses powered by the same LPS MG. This four-page concept is illustrated in Fig. 5, which shows just one of the four pages. The display is organized from top to bottom as follows: a menu, EE power, the surge battery, emergency battery, and finally the MG power.

The layout, particularly the location of the labels and the arrangement of the battery charge indicators and their readouts, was partially inspired by the EICAS display from the Boeing 747-400 [39]. For a hybrid aircraft like SUSAN, this layout is logical. For example, if the generators are conceptualized as a "cause" and the EE power as an "effect", during a malfunction, by scanning from top to bottom the crew can find the symptoms and then the culprit.

1. Color Coding

The four bus groups are identified by color instead of number, taking advantage of another graphical dimension to convey information. Green, blue, yellow, and red were chosen for their distinct relative contrast. As an example of color-coding, in Fig. 5, the symbols are themed blue as a way to identify with the blue bus. Similarly other pages will have green, yellow, and red themed symbols of identical form. The use of red and yellow is arguably risky, as the crew may mistake a warning, typically displayed in yellow, amber, or red, for the normal color of a symbol, thus overlooking a warning. However, as unconventional as color-coding may seem, its employment is not without precedent and in fact rather prevalent on aircraft of British pedigree. For instance, the DH Comet highlighted the dials at the flight engineer's station with the aforementioned colors to distinguish between its four hydraulic systems, and a similar setup (albeit with three colors) can be found on the HS-121 Trident and Concorde [40]. Color-coding the hydraulic system as a practice was then inherited by Airbus [40, 41] and applied to their digital display, although only as a naming convention (the hydraulic lines are not colored according to their name on the display) [21, 42]. The displays proposed herein leverage colors to a much further extent than Airbus.

2. Energy Centric Theme

In order to enable intuitive conceptualization of the behavior of the hybrid system, an energy-centric theme unifies the indicators. All indicators convey information about energy, such as how much energy is being produced, stored, and consumed, and the respective rates (rate of change of energy with respect to time is power). The theme can be thought of as a mental framework upon which the crew can conceptualize each component as an energy producer, storer, and consumer. The framework builds a broader picture of where energy is flowing. Forming this conceptual overview is

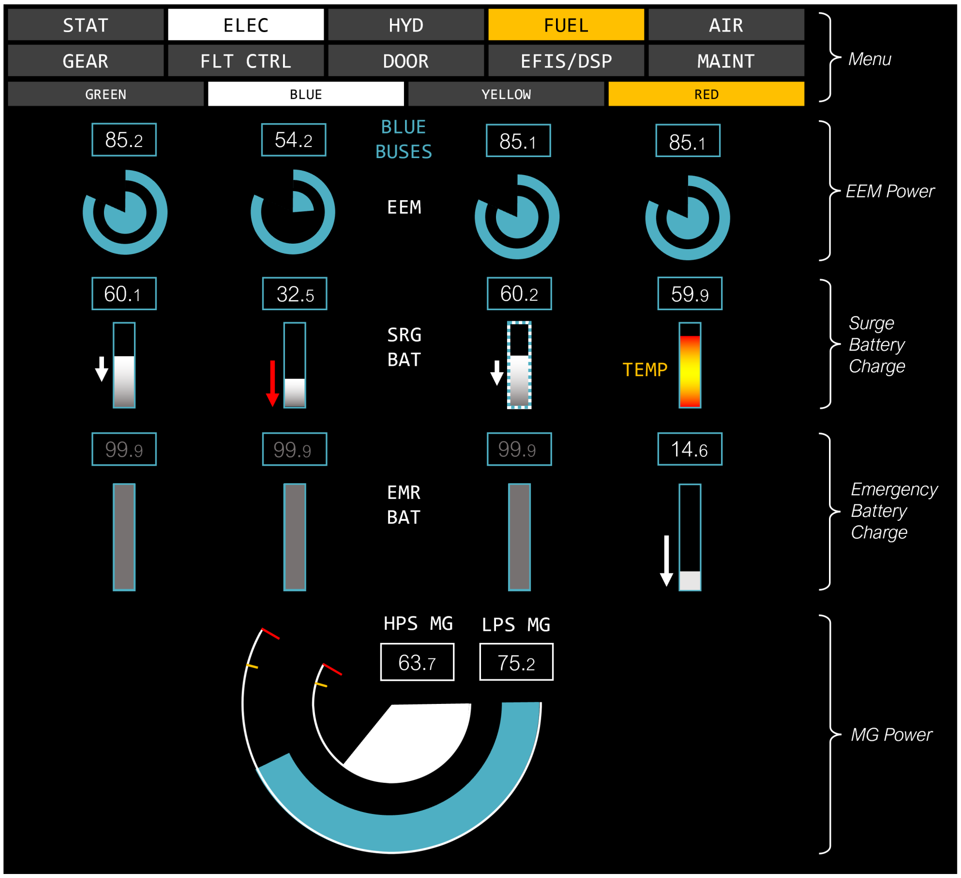

Fig. 5 Example of a HESD concept displaying components connected to the blue LPS MG. The rightmost surge battery has overheated, triggering a temperature warning, and activating the emergency battery. The left inboard battery is also indicating an abnormally high discharge rate with a red discharge indicator.

not possible if the components are inconsistently characterized. Since the space constraint prevents a depiction of the wiring diagram on the display, a solid and unambiguous understanding of the hybrid system's behavior is paramount.

Energy is deemed more relevant to the crew as automation already monitors voltage and amperage in the background. Energy characterizes the power produced for propulsion but also the remaining endurance in an event of a turbofan failure. Consequently, information typically shown on a traditional electric synoptic display, such as voltage or amperage, can then be omitted without sacrificing the crew's ability to understand system health and status. This energy-centric approach thus liberates valuable space needed for a complicated electrical system like SUSAN's.

3. Qualitative Information

The design seeks to convey information qualitatively (dynamic pointers and bars), instead of quantitatively (precise digits), by leveraging intuitive symbology and color-coding. This is because in many cases quantitative information is not necessary to provide situational awareness, and qualitative information generally occupies less space because digits must be large enough to be readable. Quantitative information also requires the crew to recall from training or reference a checklist to see what the nominal values are to evaluate the information. This may increase training time and cognitive load, which renders the display and crew interaction more vulnerable to human error. In fact, a human-factors report from Lockheed [43] recommends to, "present information graphically, where appropriate, using techniques that relieve the need to read and interpret alphanumeric data," and to "Present digital values only when knowledge of numerical value is actually necessary and useful."

Elements of this qualitative shift in focus are already apparent in the evolution of electrical synoptic displays. For example, the 737 Classic, an airliner family from the mid-80s, has an AC & DC Metering Panel installed in the cockpit overhead panel to display the voltage, amperage, and frequency for multiple buses and power sources [44, 45]. On more modern airliners, with software safeguarding the electrical system in the background, these quantities can be withheld from the crew as the information is not actionable. On the 777 and 787, voltage and amperage are displayed only for the main and APU batteries [46]. Their displays instead prioritize conveying the status of each component and where power is flowing. The displays shown herein attempt to extrapolate this trend.

Accordingly, digital readouts are minimized. Only the power of the EEM, MG, surge battery, and emergency battery are represented with a readout. Readouts here are necessary because these parameters are critical to the internal energy management of the aircraft. The style of boxing the digital readouts was adopted from Boeing [39, 44, 46]. The boxes serve to visually highlight the digits and display them in an expected and consistent location. Adopted from Airbus, the digit behind the decimal is in a smaller font [21, 42] presumably to focus attention on the larger leading digits.

In the digital readouts, values with units are wholly avoided and presented as a percentage instead, normalized against some maximum limit, which may change with flight condition but is computed in the background. A FAA design guide states [25], "Information shall be presented in a directly usable form, that is, [users] shall not have to transpose, compute, interpolate, or mentally translate the information displayed into other units." Percentages are easy to understand and reduces memory load on the flight crew, minimizes interpretation error, and may even reduce training time and cost.

4. Synoptic Page Selection

The desired synoptic page to be displayed on the MFD can be selected with a menu, similar to what can be found on the 777 or 787 [46]. The menu consists of tabs for each page, and the page currently open is highlighted white. The behavior is almost identical to the tabs of a web-browser and should be intuitive and self-explanatory. It is assumed SUSAN, just like modern aircraft such as the 787 [46] or A350 [21], will have a cursor to click within the User Interface (UI).

When the ELEC tab is selected to view the HESD, a third row of tabs appear beneath the main menu to allow the pilots to switch between each MG page. The fault annunciation behavior is again similar to the 787's menu [46]. If a fault appears in a page that is not currently being viewed, the associated tab will be highlighted amber to capture the crew's attention. This warning system is necessary since the entire aircraft cannot be monitored from a single page, so failures may be hidden. The MASTER CAUTION annunciator and an error message on the EICAS will also direct the crew's attention to the MFD. The relevant page can also pop-up automatically. In Fig. 5, the red electrical system and fuel system each contain a fault, so their tabs flash amber. Once the crew acknowledges the warning (usually done by pressing the MASTER WARNING light), the flashing ceases but the tab remains highlighted in amber.

5. EE Dials

Beneath the menu are four circular EE "pie" symbologies (blue in the example in Fig. 5), which consist of two pie charts stacked concentrically. For each EE there are two EEMs, so each pie indicates the power consumed by each EEM. The concentric pies not only occupy less space compared to placing them adjacently, but they also depict how both EEMs are on the same rotational axis. Digital readouts, indicating the average power of the two EEMs, are situated on top of the pies for a precise indication of engine power, eliminating the need for the pies to have a scale, which would be unreadable at such a size. This allows the pies to be minimalistic, alleviating visual clutter. Each digital readout indicates the average percentage power of the two EEMs.

From among RPM, thrust, and power, power was chosen as the parameter to best characterize the status of the EEMs, primarily because power conformed with the energy-centric theme. There are still further justifications. While RPM is simple to measure and ubiquitous on propeller driven aircraft, it is the least elucidating parameter, as the same RPM does not equate to the same thrust or power when airspeed varies. Thrust is an intuitive parameter but fails to represent the energy being consumed by the motor, as less power is required to produce identical levels of thrust at lower altitudes. Finally, power is not only relatively simple to measure but also more relevant to the electrical system. Power is arguably as intuitive to the crew as thrust.

6. Battery Charge Indicators

The bars underneath the engine pie indicate the battery charge. The top row of bars is for the surge battery and the bottom row for the emergency battery. The emergency battery bars are longer than the surge battery bars to reflect their greater capacities, allowing the crew to intuitively identify the type of battery without reading the label. One of the surge batteries (right inboard on the blue system) also has a permanently dashed border to indicate its connection to the

HPS MG. The "filling" of the bar features a slight gradient to highlight the top edge.

SUSAN is envisioned to have an extensive cooling system to regulate battery temperature. However, to further conserve space, no dedicated scale or digital readout exists for the battery temperature. Battery temperature is not controllable by the crew so a detailed indicator is not necessary. Instead, if a battery overheats, its respective bar turns orange, and a TEMP warning appears, as shown in Fig. 5. Inactive batteries and their readouts are greyed out akin to the common practice of greying out inactive fields in software UI [47].

Depending on direction and magnitude, the arrow next to the battery indicates the charge or discharge rate. They effectively act as both a qualitative ammeter, and from the energy-centric theme, an indicator of the power the battery is providing. If the current were to exceed a certain limit the arrow turns red. With automated safeguards, the arrows may not be necessary as the battery could be disconnected without pilot action.

7. MG Dials

Finally, at the bottom of the display are the concentric pies indicating the percentage power generated by the LPS and HPS MGs. These pies are styled almost identically to the engine pies found on the Boeing 777 and 787 with the yellow and redline limits demarcated. Perhaps the only novel concept present is the concentricity. Similar to the EEM pies, the concentricity reflects the co-axial arrangement of the HPS and LPS. The HPS MG indicator is at the center as the HPS is located in the core of the engine and has a smaller diameter than the LPS. While the concentric arrangement does not supply more information per se, it allows for the displays to be deciphered more intuitively. The LPS MG pie is filled in with the color of the bus to represent the LPS powering the bus. The readouts are simple percentages of a maximum rated power.

8. Omission of Converters

As the display of the propulsion state is energy themed, voltage and current indications are unnecessary. Consequently the information about the converters can be excluded too. The myriad of converters operate and are monitored in the background, and if a failure does occur, an error message (such as “BUS FAULT”) along with the indication of a component shutoff should provide sufficient actionable context. The converters, which act as controllers, are portrayed as an integral part of the controlled component. For example, if an EE controller fails, the display indicates that the EE as a whole has failed. The omission of dedicated indicators for the converters is not only a consequence of the energy-centered theme, but needed to fit SUSAN’s system within the limited screen space.

9. Tradeoffs and Limitations

Partitioning the hybrid system into four pages allows for ample horizontal spacing between each element, reducing clutter and improving readability. The symbols used can be found on conventional airliners and are mostly self-explanatory. However, the Four Page HESD is hindered by a number of disadvantages. Firstly, the use of available display space is not optimized as much of the space has been occupied by the concentric MG pie. Unoccupied space adjacent to the MG pie is wasted. Next, the display provides no information about where energy is flowing; while the surge batteries are discharging, it is unclear whether they are powering the EEs or MGs. Finally, during critical phases of the flight, such as engine start, the checklist may call for the hybrid system to be monitored. With four synoptic pages for the flight crew to scan, developing a mental model of the propulsion state could be difficult. In fact, the FAA Human Factors Design Guide [25] states, "If a user needs a variety of data to complete a task, those data should be provided in an integrated display, not partitioned in separate windows." While the Four Page HESD concept possesses an allure in its minimalism, its inherent limitations were unacceptable, so work was refocused on a synoptic display that employs only a single page.

B. Iteration II: Laterally Arranged HESD

After the limitations of the Four Page HESD became apparent, a renewed attempt was made to fit the entire propulsion system state in one page. The proposed Laterally Arranged HESD is depicted in Fig. 6, which organizes the components left to right in reference to their physical location on the wing. Instead of pies, EE power is indicated by eight crescents at the top row. Beneath the EE indicators are 16 columns of battery indicators. Finally, the MG indicators are situated at the bottom of the display.

Miller’s Law is an psychological observation that the human mind has difficulty remembering simultaneously more than seven pieces of information [48]. Miller’s Law is often interpreted in UI design as a guideline against placing more

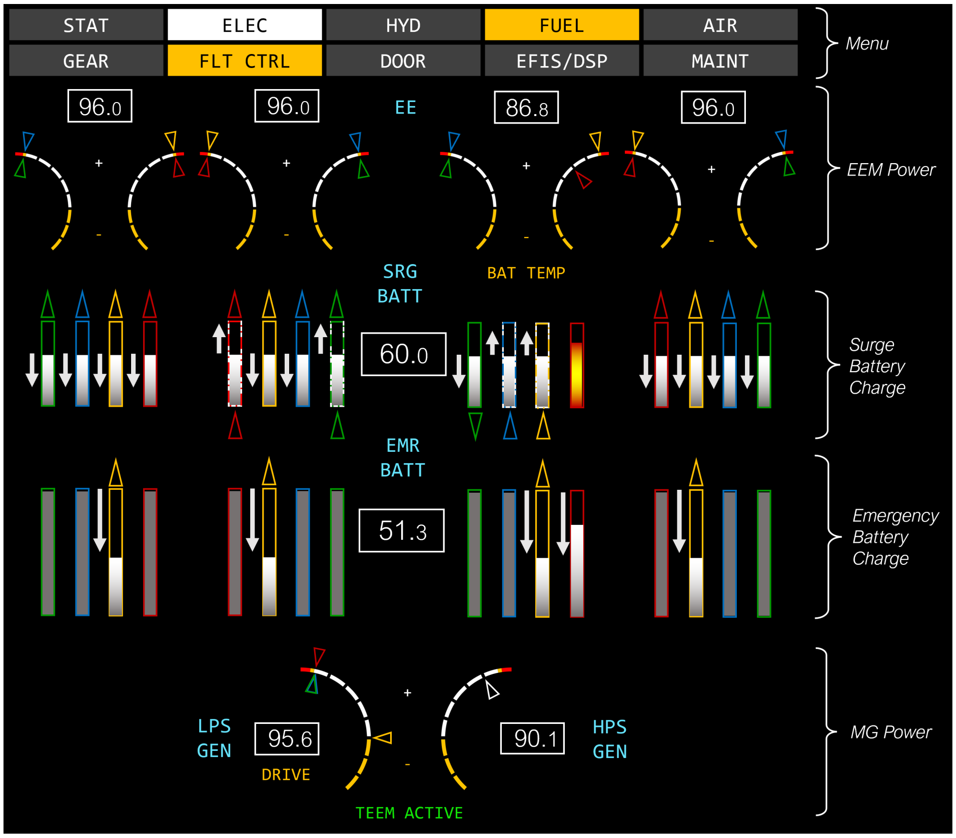

Fig. 6 Laterally Arranged HESD. In this example, the yellow LPS MG has failed, so the emergency batteries on the same bus are powering the yellow motors. Additionally, one of the red surge batteries has overheated. The tabs on the top row also indicate a warning in the fuel system page.

than seven elements together [27]. With 16 copies of each component, an unorganized display will thus produce high cognitive load when the crew tries to read the entire screen. Accordingly, the 16 columns are not evenly distributed across the width of the screen but rather clustered into four groups. In UI design, the use of clustering and grouping to address Miller's Law is in fact an application of the Law of Proximity, which states that elements placed in proximity are implicitly grouped together and perceived to represent similar functions [27, 28].

This design heavily leverages clustering both in the row-wise and column-wise direction to organize the high multiplicity of information. In the row-wise direction, while there are still 16 battery indicators per row, they are divided into a hierarchy of four main clusters. Each cluster contains batteries from all four buses. The clusters are depicted as "belonging" to the boxed EE power readout at the top, which averages the EE power from all four buses. Meanwhile, the negative space in the column-wise direction visually separates the EE dials, surge batteries, and emergency batteries, improving organization.

1. EE Dials

As discussed in the previous section, the main obstacle preventing the entire system from being displayed on one page was the insufficient space for 16 circular EE dials to be placed adjacently. Bar-style indicators, such as those displaying battery charge, are much thinner than pies or circular dials, so the approach initially considered was to use battery-charge style bars for the EE power as well. Although it is possible to fit 16 bars adjacently, overusing bars may risk the crew mistaking a power indicator for a battery charge indicator. To maintain the energy-centric theme, it is also preferable if bars are used to indicate energy storage while energy flow (power) is indicated differently. Thus, alternate methods of displaying the engine power were explored.

Multi-engine piston aircraft often feature dials that are shared by overlapping needles to indicate information about multiple engines on a single dial face. A proposed multi-engine dial was designed with the same approach (Fig. 7),

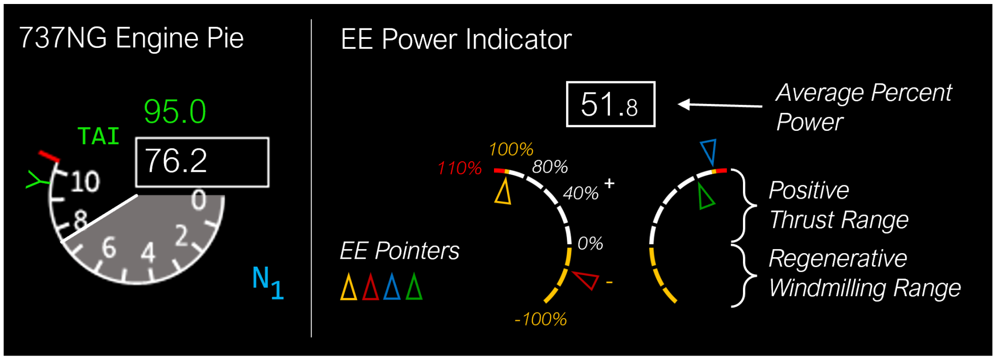

Fig. 7 Engine pie used on the 737NG and Max [44] compared with the dial proposed for the HESD, which can display information about four separate EEs while occupying a similar width. Italicized text are annotations.

which displays the power of four EEs while occupying similar width as a conventional engine pie. Just like an analog dial, the position of each pointer indicates the power of the EE, the average of both EEMs. To declutter the display, there are no longer individual indications for the power of each EEM. The crew cannot control the EEMs individually so the information is not actionable.

Double-crescent scales were employed to preserve the relative lateral position of the EEs regardless of power level. For instance, in Fig. 7, the yellow, red, blue, and green engines are positioned left to right respectively. While it is geometrically possible to condense the display further such that all 16 EEs use the same scale, the EE lateral location would no longer be evident. With a quartet of these dials laid out in a row, information about all 16 EEs can be displayed.

Color coding is once again widely exploited. The pointer's color indicates the bus the EE is connected to, eliminating the need for text labels and saving additional space. The upper white portion of the crescent scale indicates positive thrust while the lower yellow portion indicates negative thrust, which occurs during reverse thrust or regenerative aerobraking. In addition to these color cues, 0% power is intentionally fixed at the horizontal for quick recognition of whether the engine is thrusting (upper range) or braking (lower range). Although regeneration has yet to be implemented into SUSAN's architecture, the symbology was designed for applications on hybrid aircraft in general. The idea of dividing the crescent into two regions was inspired by displays found on German ICE high speed trains, which also feature regenerative braking [49]. In between the two crescents are "+" near the upper range to indicate positive power and "-" near the lower range to indicate negative power. Breaks in the crescent act as minimalistic tick marks to represent 20% increments in power. Compared to the 737NG's conventional tick marks (Fig. 7), this style of tick marks uses negative space to create a less visually intrusive design.

To conserve space, only four digital readouts for the engine power exist, each representing the average power of the group of four EEs in the pair of crescents below them. While averaging the engine power departs from convention, the pilots are not expected to have individual control over each EE, and the crescent scales still provide information about the power of an individual EE. The tick marks are not numerically labeled unlike the dial on the 737NG (Fig. 7). These numbers would be superfluous as the crescent's role is to qualitatively reinforce the digital EE power readout.

2. Battery Charge Indicators

Located below the row of crescent dials in Fig. 6 are the charge indicators for the surge and emergency battery, which behave similarly with those from the Four Page HESD. Similar to the EEs, the batteries have their borders color coded according to the bus they are connected to. Color coding saves significant space compared to other alternatives such as abbreviated labels or a bus diagram connecting the batteries to the MGs and EEs.

Boxed readouts, located at the center of the display, show the average charge across only the batteries that are active. For example, in Fig. 6, most emergency batteries are fully charged, so the emergency charge percentage shown at the center only accounts for the discharging yellow and red batteries. SUSAN's buses are not interconnected, so once the emergency batteries on the yellow buses are depleted, the yellow EEs become unpowered. Including the charge of inactive emergency batteries from healthy buses in the average misrepresents the usable charge remaining in such a contingency. Selective averaging will be adopted in subsequent displays herein.

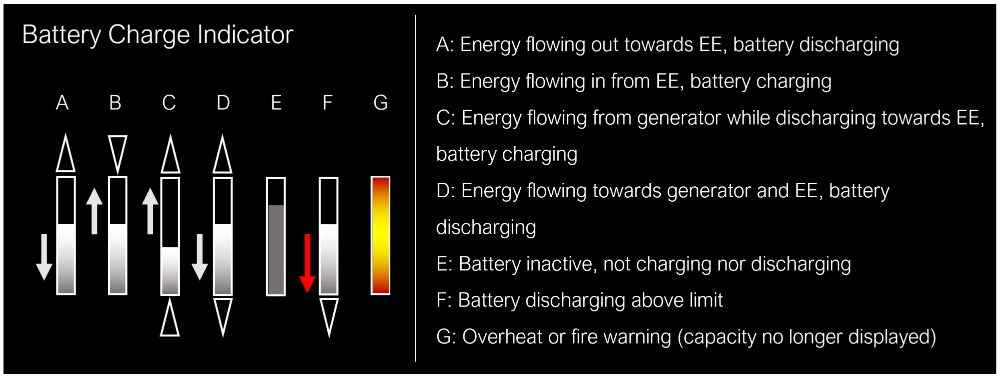

Fig. 8 Examples of the battery charge indicator in different situations.

3. Energy Flow Indicators

Depicting the flow of energy between each component is essential in an energy-centric display. Early in the display's development, an idea existed to connect each component with arrows that indicate the direction energy is flowing, akin to both a wiring diagram and energy monitor display found on hybrid cars which shows how energy flows between the battery, motor, and gasoline engine [50, 51]. However, space constraints forced same-bus components to be aligned on the same column. For instance, an arrow connecting the emergency battery to the EE or the MG to the surge battery would be impracticable as the direct path on the layout is obstructed, so an alternative solution was pursued.

Triangular pointers situated above and beneath the charge indicators were devised to indicate energy flow. These pointers are a condensed alternative to a wiring diagram. Examples of how these pointers operate can be found in Fig. 8. Generally, a triangle pointing towards the battery portrays energy flowing into the battery while a triangle pointing outwards portrays discharge. These scenarios are not mutually exclusive because the surge battery could be simultaneously charged by the LPS MG while discharging into the HPS MG. The pointer on top indicates the direction power is traveling between the battery and EE, and the pointer underneath indicates the same between the battery and the MGs. If the batteries are inactive, no pointer will appear. The pointers are only feasible because of color-coding, without which the space above and below the batteries would be occupied by text labels or graphical lines that are necessary to indicate which bus the batteries are connected to.

4. MG Dials

Located at the bottom of the display in Fig. 6 are the LPS and HPS MG dials that display the power generated by the MG. These have the same design as the EE dials aside from four pointers sharing the same crescent on the left LPS scale. Recall that each LPS MG consists of four separate windings feeding four buses. All four outputs per MG are averaged under one pointer to reduce clutter. When the MG generates power, the needles are in the positive white band, and when the MG motors, the needles are in the negative yellow band. Akin to the EE dial, the "+" and "-" indicate positive or negative power being generated. For both the EE and MG dials, the "+" and "-" signs can be interpreted as energy flowing out of or into a component. Power, instead of voltage or amperage, was chosen because the display is energy focused, and power is normalized as a percentage.

In Fig. 6, the yellow LPS MG is depicted as failed. The LPS MG power indicator indicates still 95.6% as the readout only averages for the 3 LPS MGs left online. The failure of the yellow LPS MG is indicated by the neutral position of the yellow indicator. Similar to typical airliners equipped with an integrated drive generator, the crew can disconnect the clutch between the engine and generator upon encountering an issue [52], which then triggers a "DRIVE" warning [39, 44, 46].

5. Tradeoffs and Limitations

The most apparent advantage of the Laterally Arranged HESD is its ability to render the entire system on a single page. Another advantage of the layout is the preservation of the relative lateral position of the system components (hence its name). For example, during an EE failure, the crew can readily identify the failed unit's distance from centerline and judge the asymmetric effect on flight handling. As another example, during a battery fire that propagates to neighboring units, the crew can see batteries and motors fail along the span of the wing on the display, which may allow for a quicker diagnosis.

However, the use of energy flow pointers is not intuitive. Deciphering it requires memorization of SUSAN's specific architecture. For example, a pointer indicates that power is flowing upwards from the emergency battery (as shown on the leftmost yellow bus in Fig. 6). Without remembering that the emergency and surge batteries are not connected, the arrow can easily mislead the crew into thinking the energy flowing out from the emergency battery into the surge battery. While the arrows show from where energy is flowing away, it does not indicate to where the energy goes.

Additionally, this concept is feasible only with the widespread and unconventional employment of color-coding. Stylistically, the columns of alternating colors may be too visually aggressive. The usage of blue pointers against a black background is also not recommended by various display design guidelines due to its low contrast and luminosity [32, 33]. Yet the most critical color issues stem from the lack of color blind accessibility. Depending on the degree of the color blindness, the multicolor EE or MG pointers could become indistinguishable. The display also suffers from a deficit of text labels that indicate which color each column represents. 16 annotations simply could not be fit on top of each column without interfering with adjacent labels. Overdependence on color deprives the display of essential color blind accessibility, and such a critical deficiency would likely preclude it from certification.

The convention of reserving red and yellow for warnings (as specified in 14 CFR 25.1322 [53]) is violated. The FAA warns [33], "If red and yellow/amber are used too broadly, pilots may become desensitized to their meaning and not be able to recognize situations quickly where their actions are time-critical. Additionally, inconsistent use of red and amber / yellow can lead to difficulty interpreting the meaning of the colors when they appear, resulting in a slower response and increasing the potential for a more significant error." The prevalence of red and yellow may mislead the crew into believing an error exists with the yellow or red components and disabling the bus unnecessarily. Alternate colors such as purple or orange were considered, but they exhibit insufficient contrast in hue to magenta or yellow respectively, and magenta is already reserved for autopilot indications. To address both color blind accessibility and improve the energy flow monitoring, the final synoptic layout was then devised.

C. Final Iteration: Compartmentalized HESD

The Compartmentalized HESD (Fig. 9) redesigns the layout to visually connect the components together. Like the Four Page HESD, the layout is grouped by electrical bus rather than physical position, while the information is presented on one page like the Laterally Arranged HESD. The display is compartmentalized into four distinct and independent columns, each containing the components from the same bus color (same electrical system). The display no longer depicts the actual spanwise location of the components but this tradeoff is well worth the layout's advantages. The energy-centric theme is even more apparent and the symbology inherits many of the same omissions and simplifications from previous concepts.

This display's design is chiefly driven by the novel idea of compressing information to simplify the display. The FAA recommends that the information conveyed per unit area of the display be minimized [24, 25], but SUSAN's complex architecture inevitably drives up the information density given a fixed display area. However, information density can be curtailed if the amount of distinctive information presented is reduced. During normal flight, all similar components typically operate at equal power or charge. A certain power reading, or battery charge, is replicated 16 times. It is unnecessary to present so many replicates of the same information. Only when a deviation occurs, such as during an component failure, does the behavior of a particular component become important. The layout relies on compressing the quantity of information displayed by hiding or removing the distinction between redundant information, analogous to how electronic files are compressed. The indicators, which will be discussed in detail shortly, are designed to compress information while still retaining the ability to indicate the behavior of any individual component that diverges.

This principle of compression naturally declutters the screen during nominal operation, reducing cognitive load. This is shown in Fig. 9, which depicts normal functioning of the hybrid system. Each of the four compartments is highlighted by a colored background, representing the color of the bus and components represented inside. For instance, the green compartment actually hosts four green buses, but the symbology is designed so that when all four buses and their components act in unison, only a single green bus, EE, surge, and emergency battery are depicted. As Fig. 9 shows, under normal circumstances the entire synoptic display shows only four systems and is much simpler to read than previous displays, even though in reality all 16 buses are presented at once. This reduces the amount of information the crew must normally read.

Meanwhile, the display is still fully capable of providing the crew an accurate overview when components in the same compartment deviate in behavior. Fig. 10 illustrates the full capability of the synoptic display in depicting off-nominal situations. Comparing Fig. 9 and Fig. 10 provides a perspective on how information is compressed in

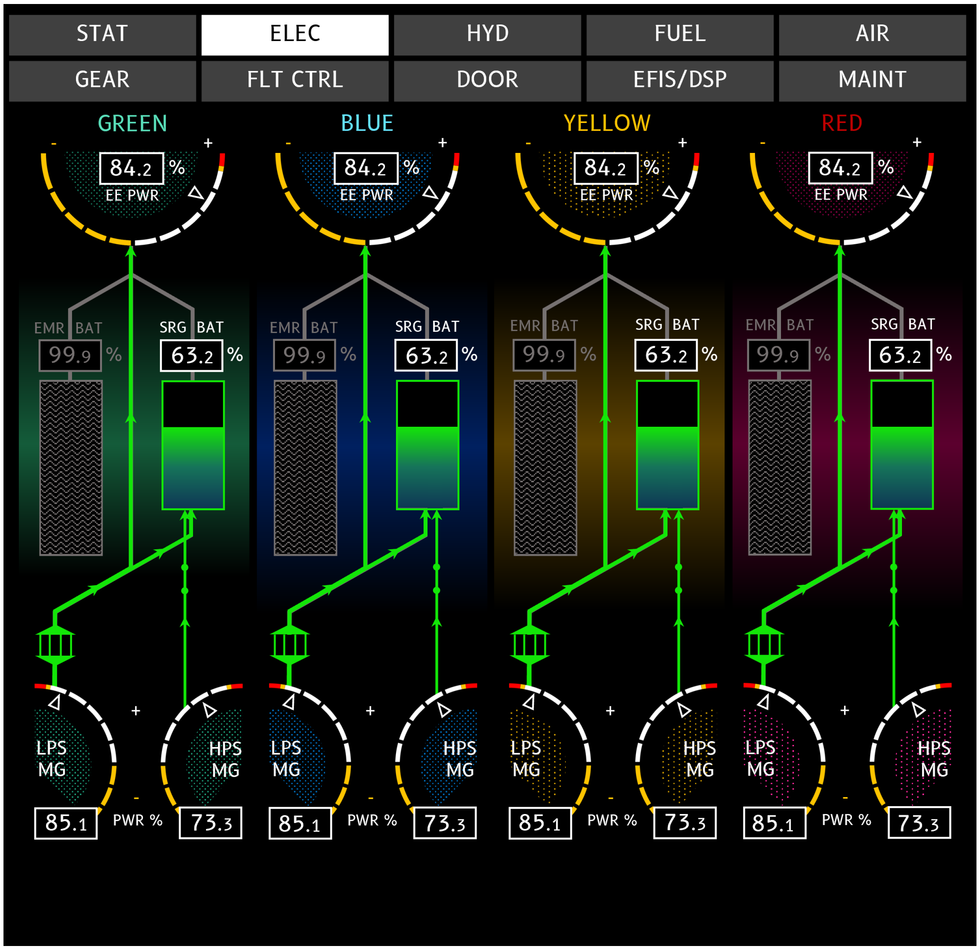

Fig. 9 The Compartmentalized HESD under normal flight conditions. Instead of presenting 16 buses explicitly, the principle of compression gives the impression that there are only 4 main systems to monitor. The display features the recent B612 font developed by Airbus [54].

normal operation while distinctively emphasized in an emergency. What the symbologies in Fig. 10 depict will be discussed in dedicated sections below.

1. Routing Diagram

One of the most significant improvements over the previous iteration is the ability to depict inter-component connections with a bus diagram and their energy flow with arrows. The bus diagram intentionally resembles the visual styles from conventional airliner synoptic displays, but the use of arrows is novel. With the architecture explicitly mapped on screen, as opposed to being implied as in the Laterally Arranged HESD, the diagram is more intuitive to decipher and requires no memorized knowledge of SUSAN's system layout.

The depiction of the architecture is infeasible on a Laterally Arranged HESD owing to how SUSAN's architecture distributes components powered by each bus evenly across the wing. This would result in a spatially expensive maze as evident in Fig. 2. The compartmentalized layout surmounts this problem by placing components of the same color in close proximity, effectively untangling the connections and shortening their pathlengths, which permits the paths to be straightforwardly illustrated in the available space.

An annotated example of a single compartment can be found in Fig. 11. Just as before, energy flows from the MGs at the bottom to either the surge battery or directly to the EE dial at the top. The main difference is that the batteries and EEs are presented as if they are a single component connected to a single bus. It is important to remember that each route, with the exception of the connection between the HPS MG to the surge battery, summarizes the behavior of four

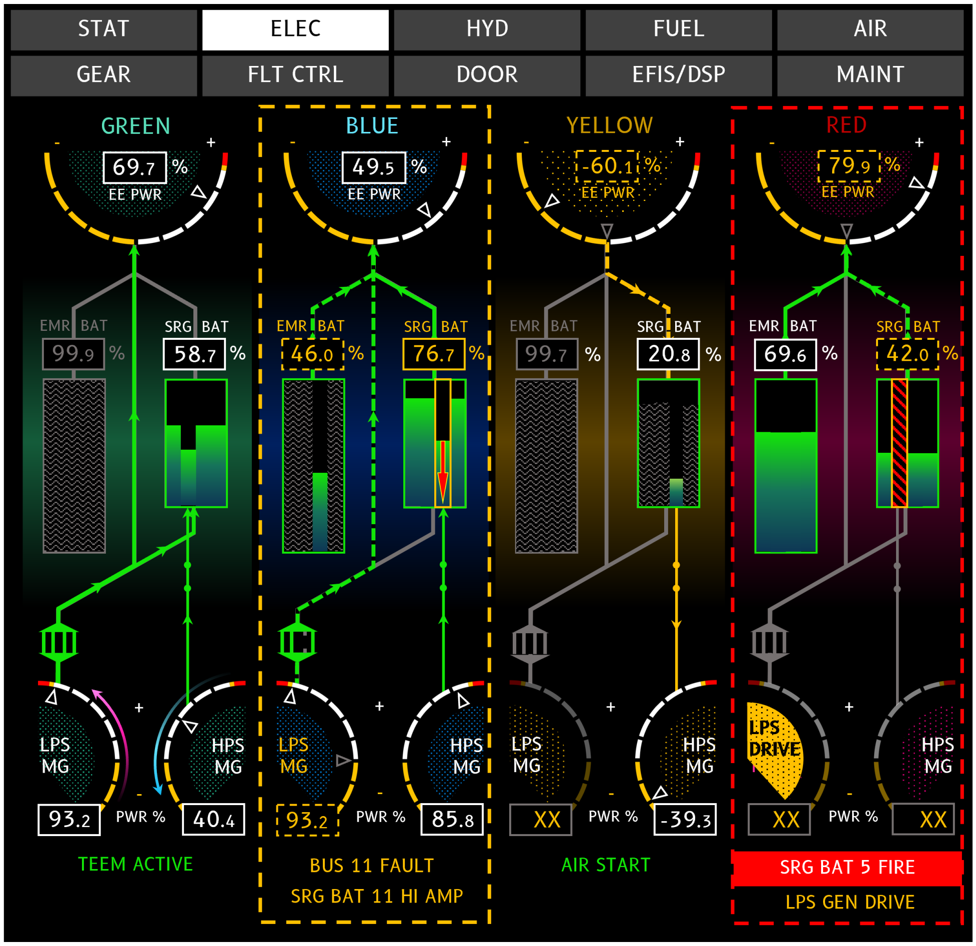

Fig. 10 The Compartmentalized HESD in off-nominal operation. Each compartment depicts a different situation. The behavior of each individual bus is now visible.

buses. The EE dial also hosts the power of four EEs.

If one of the four buses deviates in behavior, the arrow that shows the energy flow becomes dashed. To clarify which bus is deviating out of the four, a bus state indicator is located right above the LPS MG dial that splits the route into its four constituent buses and indicates their state with color. This indicator acts like a magnifying glass to view the energy route's underlying behaviour. Examples of the bus state indicator operating in different situations are provided in Fig. 12, which also shows how the color and direction of the arrow changes. Solid arrows indicate all four buses are behaving in unison while dashed arrows indicate one or more buses has deviated. Inactive buses are greyed out.

The use of arrows on bus diagrams is not standard to aircraft synoptic displays since energy typically flows in one direction on non-hybrid aircraft, but the hybrid architecture's ability to manipulate energy flow necessitates more visual clarification. As mentioned previously, the idea was inspired by energy monitoring displays from hybrid cars. In fact, depicting energy flow with arrows has already been implemented on the Toyota Prius for at least two decades [51]. Similar to certain variants of the car, when power is flowing upwards on the display towards the motors, the flow is highlighted green, and when power flows downwards towards the generators or batteries, the flow is highlighted amber. This allows the crew to rapidly recognize if the system is outputting or receiving energy.

2. EE Dials

The power of the four EEs of the same color is indicated by the EE dial at the top of the display, and a digital readout provides the average power of all working EEs. Several concepts were explored in designing the EE dial in an attempt to simplify it further. These concepts, illustrated in Fig 13, compare the idea of presenting all four pointers for four EEs

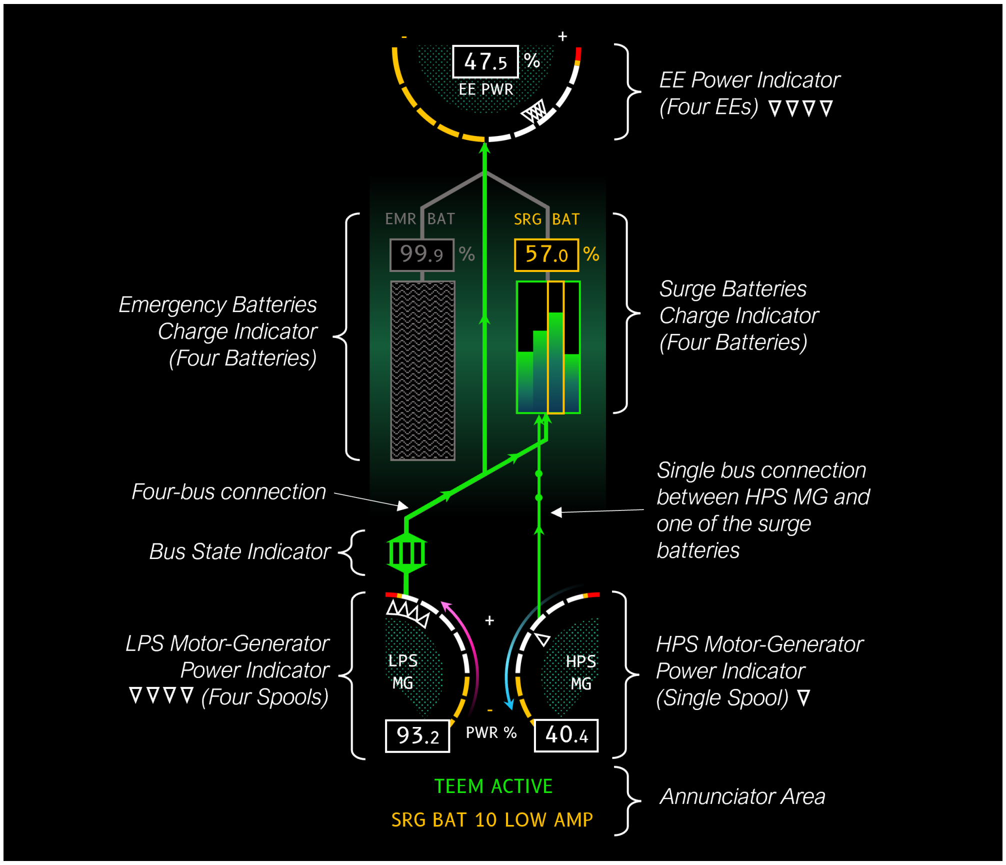

Fig. 11 A single compartment of the display.

(dial A) versus displaying just the average power (dial B), the range (dial C), or a combination of both (dial D).

In these examples all dials show the same situation with highly abnormal power settings on each EE to test the validity of each design. Notably, one EE has failed and produces no power while another one is in regenerative mode. In dial A, which indicates separately the power of all EEs, the failure is clearly indicated by the greyed-out pointer. Dials B to D employ different methods to reduce the number of pointers, but the failure of one EE becomes obfuscated. Since dial B only shows one pointer that depicts the average power, it misleadingly provides the indication that all four EEs are producing a lower power. Dial C provides the average with a white pointer and the grey band shows the range in which the minimum and maximum powers have deviated from the average. While it can be concluded here that an EE is in regenerative mode, it is not apparent that an EE has failed. Dial D brackets the range of power between all four EEs with red (minimum) and green (maximum) pointers. Even less information is conveyed by Dial D, and it suffers the same issues as Dial C.

The omission of critical information (an EE has failed) in dials B to D is too expensive a tradeoff for simplifying the EE dial, so the simplest option is to avoid averaging the data altogether and use dial A. Clutter is a trivial issue because in normal conditions when all four EEs consume nearly the same power, the pointers in dial A overlap and merge as a single pointer. This is a very straightforward example of how the dial simplifies itself and an example of information compression. Fig. 14 shows how when one EE's power deviates from the other three (in the case of a malfunction or failure), one of the pointers will emerge from the overlap. The digital readout along with its outline also plays a role in highlighting a deviation.

One weakness of the dial design is the lack of a numeric label indicating which pointer represents which EE. Originally numbers attached to the pointers were envisioned, but space constraints prevented this implementation. Numbers attached to the pointer will also overlap if pointers overlap (as is usually the case), rendering them illegible. However, the always-visible EICAS can clarify which specific EE has failed, as it provides a more detailed overview of the propulsion state.

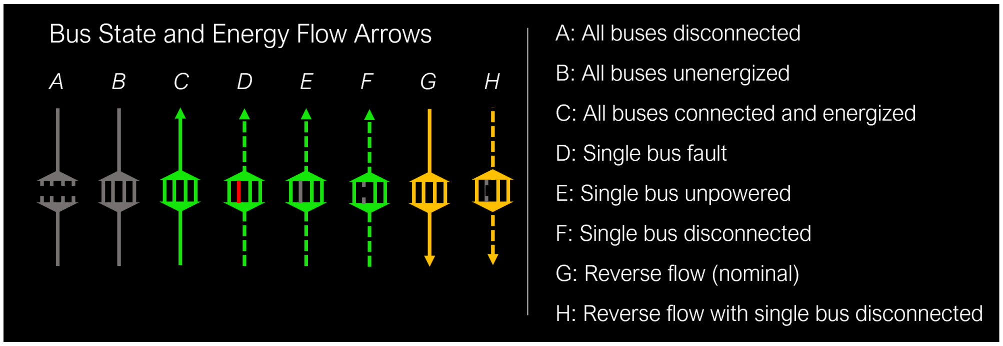

Fig. 12 Examples of how the bus state indicator and energy flow arrow function.

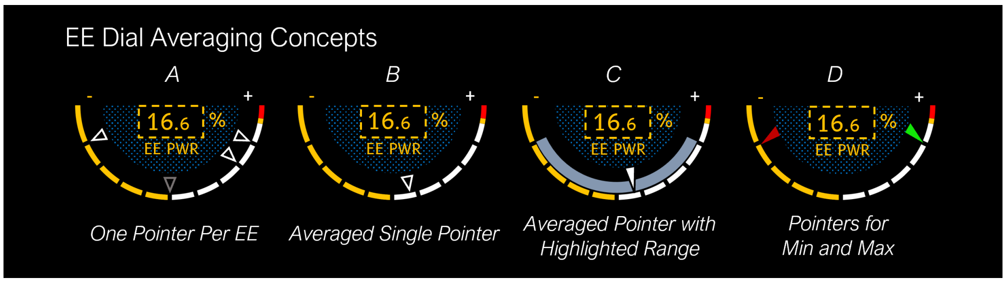

Fig. 13 The four concepts explored for simplifying the EE dial. Digital readouts are in amber because one EE has failed.

3. Battery Charge Indicators

While the battery charge indicators still employ intuitive bars, their organization differs from the previous iteration. Examples of how the charge indicator functions are illustrated in Fig 15. As an example of compressing information, the charge indicators for the four batteries are packed adjacent to each other in a larger box. Here compression does not mean that the indicators are compressed against each other visually, but rather that when all batteries indicate the same charge and align, the distinction between the individual bars disappears, forming one larger battery indicator (Fig 15 example C). This reduces the amount of information the crew must absorb. The box acts as a single charge indicator for all four batteries unless there is a deviation.

Another benefit of packing the battery charge indicators closely is that if a battery deviates in charge from the other three, the deviation is obvious as the bars no longer align. In this case, the gradient shading of the charge bars also helps distinguish each charge bar when they are at different heights. This effect is apparent in the surge battery indicator in Fig 11. When adjacent bars are not aligned, the color difference due to the gradient shading creates a visual border.

When a battery has a fault (Fig 15, examples D and E), it is outlined by a yellow box. The nature of the fault is specified by a warning message located at the bottom of the compartment. Example E illustrates a battery fire, which is a critical scenario. The charge indicator is filled with a highly-visible red barber pole pattern. The pattern always fills the indicator regardless of charge because the remaining charge in a disconnected and burning battery is not usable.

Packing the batteries together also conserves enough horizontal space that both the surge and emergency battery indicators can fit next to each other rather than one above the other as in the Laterally Arranged HESD, which liberates vertical space. The minimization of the footprint of each element reduces information density by creating visual space between the batteries and the MG indicator. This space is only occupied by the connections and the bus state indicator.

Finally, the charge and discharge arrows introduced in the previous iteration (Fig. 8) have been omitted to further simplify the display and reduce cognitive load. With automatic management, the crew does not need to know the amperage of the batteries in normal operations. Only in the case of an abnormally high discharge or charge rate will a red arrow appear, overlaid on the charge indicator. An example where a high discharge current is detected is shown in a situational example (Fig. 10, surge battery 11).

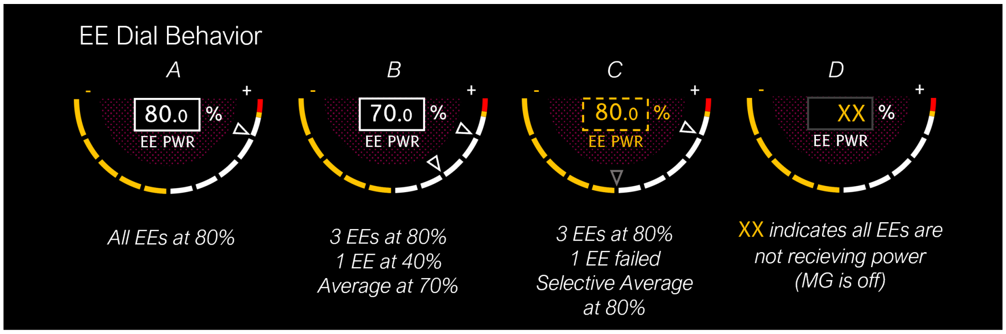

Fig. 14 Various deviations between EE power shown on the EE dial. The MG dials work in the same fashion.

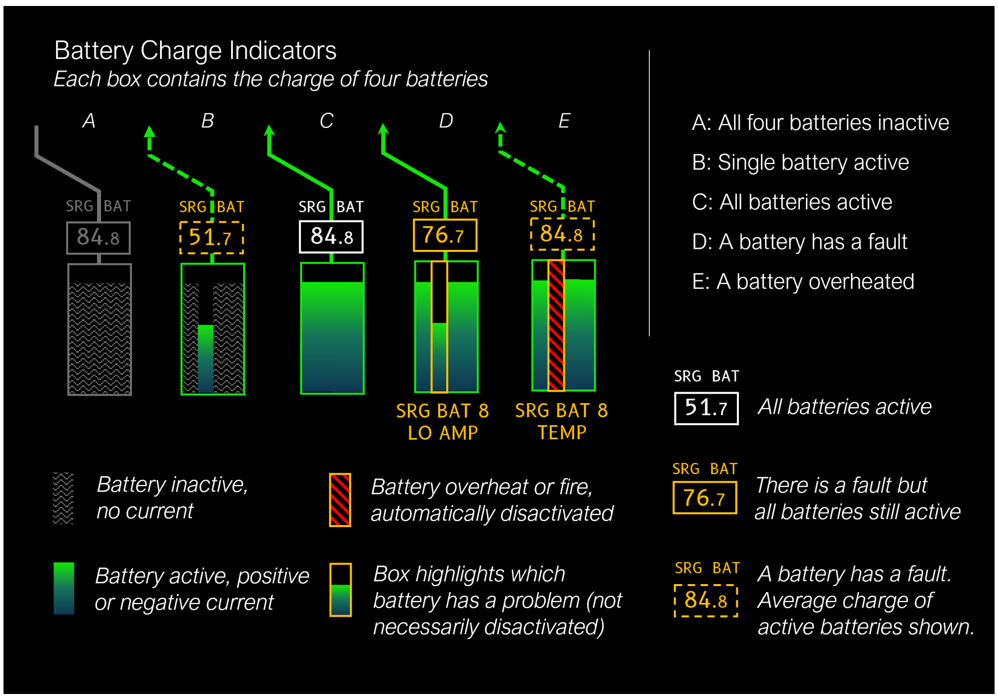

Fig. 15 Examples of the battery charge indicator and its various warnings.

4. MG Dials

Each compartment hosts its own dedicated LPS and HPS MG dials which function identically to the EE dials. The familiar double-crescent is inherited from the Laterally Arranged HESD. The LPS MG dial indicates the four outputs from the generator to each bus while the HPS MG dial only has one output as only one bus per system is connected to the HPS MG. Although the Laterally Arranged HESD used just two MG dials while this design uses eight MG dials, this tradeoff was necessary to keep the routing between the MGs and each component straightforward while avoiding complicated crossovers. Each compartment is therefore visually separated from the others such that an issue on one particular bus is unlikely to be misidentified as being on another. In the green compartment in Fig. 10, purple and blue arrows are adjacent to the LPS and HPS MG dial. These appear whenever TEEM is active and indicate whether the control is increasing or reducing the MG's power output. These arrows will be discussed further in section VI.C.7 where the situational examples are presented.

5. Warnings

In previous iterations, warning messages are located near relevant components. However, this scatters the messages across the screen. In a situation where multiple components have failed, the entire screen must be scanned for warning messages, which risks the crew missing a warning message under an urgent high-stress situation. Therefore, the warning messages are now located at a centralized and expected location at the bottom of each compartment, reducing cognitive load and reaction time. According to the Serial Position Effect, users recall information better when it is presented at the top and bottom position of a UI [55, 56]. Each compartment is read vertically following the energy flow paths, so placing the warning area at the bottom aids in the warnings being retained in memory. While the warning messages are also centralized on the EICAS, the HESD collects each warning under the affected bus.

Examples of warning messages being displayed can be found in Figs 10 and 11. Since the warning messages no longer appear right next to the relevant component, the message must specify which specific component it applies to. For example, instead of just "TEMP", "SRG BAT 2 TEMP" is more elucidating. Some messages, such as "TEEM ACTIVE", are green because they do not warn of an abnormal situation, but only provide situational awareness.

To further attract the crew's attention, whenever a yellow or red warning message appears, the entire affected compartment is also outlined by a dashed yellow or red border. The color depends on the severity of the issue (Fig. 10 yellow and red compartments). The border disappears once the crew acknowledges the warning (typically done by pressing the MASTER CAUTION annunciator on the glareshield). Therefore, in an evolving scenario where more warnings appear after, the box will only bring the crew's attention to the compartment where the newer fault has occurred.

Finally, as Figs. 14 and 15 have shown, the digital readouts also now highlight a warning to bring the crew's attention to a specific component. In both of these figures, when a component triggers a warning, both the box and digits turn yellow. If one of the components is inactive, the box becomes dashed, analogous to the previously described dashed energy flow arrows that appear when one bus is inactive. By using the menu's warning function, outlining the relevant compartment, and highlighting readouts, the display swiftly guides the crew's attention to the relevant page, compartment, and then component.

6. *Color Coding*

Another major benefit in compartmentalizing the layout is relieving the need to denote which indicators belong to which bus using color-coding, greatly ameliorating color blind accessibility. Since components of the same bus all sit in one compartment, only the compartment itself has to be labeled. The charger and power indicators themselves no longer need to be colored by their respective bus. Accordingly, at the top of each compartment the color is explicitly written in a visible size.

Color-coding by bus is still employed, but only stylistically and never on dynamic indicators. For example, each compartment is filled with a colored background matching the color of the system represented. Similarly, the dial face of the EE and MG indicators is also colored. These backgrounds and fillers are intended to accentuate each compartment so the crew can identify which system each column contains at a glance. In fact, the advantage of naming each system by color rather than number (such as "SYSTEM 1, 2, 3, 4") is evident here, because numbers cannot be used to fill a background. Naming by color also distinguishes the electrical system from the numerically labeled EEs and avoids implying that the lateral position is respected.

The background and fillers are subtle and dim to avoid distracting attention from the indicators in the foreground. For example, the background features a gradient so that it dims out at the top and bottom of the compartment, allowing the MG and EE indicators to maintain their contrast against a dark background. Since red and yellow are customarily employed for warnings, in order to mitigate conflict, dimming the the red and yellow backgrounds helps maintain a contrast between any yellow or red warnings in the foreground and the background. These backgrounds are static and are not used to deliver any other information, so familiarity with the display should render confusion unlikely. With the compartments labeled, these backgrounds are not strictly obligatory, but still aid in reading the display and contribute to overall aesthetics.

Animated indicators, such as pointers or arrows, may be color-coded but never by bus. Instead, the color only expresses the status of the component, which is already a ubiquitous practice in traditional displays. Each color consistently conveys the same meaning regardless of bus. Following convention, green and white are colors that depict nominal operation while amber and red warn of abnormalities.

Color is generally avoided as a single attribute to deliver information. The FAA recommends that, "if color is used for coding task-essential information, use at least one other distinctive coding parameter (e.g., size, shape, label)" [33]. In Fig. 15 for example, the bar representing the battery charge is filled with solid green when active. When the battery overheats, not only does the color turn red, but the pattern in the bar changes to an alternating black and red barber-pole pattern, recognizable even to the colorblind. The malfunction is also expressed by other warning messages.

7. Situational Examples from Figure 10

In the main example of the display (Fig. 10), four different situations are illustrated, one in each compartment to demonstrate the display's flexible capabilities. The green compartment depicts a nominal flight condition when the throttles are retarded and TEEM is active. In generating power the MGs produce braking resistance on the spools. When the GTE is commanded to spool down, TEEM controls the braking on each spool by adjusting the amount of power drawn from each MG in order to minimize transient excursions from the compressor operating line. Here, TEEM increases braking on the LPS by increasing the power drawn from the LPS MG. The increase in power required is indicated by the power-up pink arrow on the LPS MG dial. At the same time, TEEM prevents the HPS from decelerating too quickly by reducing the power drawn from the HPS MG, thereby reducing braking action [7, 16]. The reduction in power demanded on the HPS MG is shown by the blue power-down arrow on the HPS dial. The surplus electrical energy generated in the process of braking the LPS is routed to the surge batteries, as indicated by the green energy flow connecting the LPS MG and surge battery. The connection between the surge battery and HPS MG is green because, although the power drawn from the HPS MG is reduced during this throttle transient, the net energy flow from the HPS MG is still positive.

The TEEM related symbology, such as the TEEM ACTIVE annunciator and the power-up and power-down arrows, are arguably unnecessary since TEEM operates in the background just like any other engine or flight control law. On typical airliners, only when these laws degrade are pilots warned. TEEM is only active for the few seconds of throttle movement before the power settles to an equilibrium. This is not enough time for the pilots to comprehend the greater picture or diagnose a potential problem.

The blue compartment depicts a situation where a bus fault has been detected on bus 11, so it has been automatically disconnected. From the bus state indicator and the warning message it is evident which bus has failed. As a result, one of the pointers on the LPS MG dial is at 0% power and greyed out, indicating no power is being fed into bus 11. The emergency battery of the dead bus is activated (either automatically or by the flight crew) to maintain EE power. Without MG power, the surge battery is also discharging, but here abnormally rapidly. The SRG BAT 11 HI AMP warning is triggered, and in addition a red downward-pointing arrow over the battery indicates energy is flowing out too rapidly.

The yellow compartment illustrates an air start when the turbofan is being restarted after an inflight flameout. The example is used to demonstrate the yellow arrows, which appear whenever energy is flowing downwards on the display opposite to their nominal direction. Here, one of the surge batteries is active and discharging, sending energy to the HPS MG which is currently acting as a starter motor. The HPS power is negative to indicate it is motoring. The three other surge batteries are inactive and greyed out. One of the four EEs is windmilling in regenerative mode to replenish the charge of the active surge battery, as indicated by the dashed arrow linking the EE to the surge batteries. The arrow is dashed because only one of the four buses is energized.

Finally, the red compartment provides an example when a MG fails. The LPS DRIVE flag indicates that it is disconnected from the driveshaft. The emergency batteries have activated to maintain power to the EEs while the remaining charge on the surge battery depletes. As an example of another complication, surge battery 5 is ablaze, triggering the fire warning. The compartment is boxed in red to convey a critical emergency, and the dashed output arrow indicates only three of the buses are powered. Red warnings are reserved for the most serious emergencies such as fires.

8. Tradeoffs and Limitations

There still exist some color and contrast related vulnerabilities. A portion of the EE and MG dial are colored yellow to indicate a reversal in power. Similarly energy flow arrows turn yellow when energy is flowing towards the generator or batteries from the EE. These situations are nominal but yellow may suggest a malfunction. Moreover, the greying-out of dials or pointers, while intuitive, may not be apparent under certain ambient lighting or display contrast capabilities.

The unorthodox compartmentalization of the display concept prevents EEs and batteries from being depicted according to their physical location. Neighboring batteries on the screen are not neighbors physically. Such a tradeoff was deemed acceptable considering that on the EICAS, the EEs are still placed with respect to their lateral position. The HESD's purpose is to provide a more detailed overview of the electrical system, so accurate portrayal of the physical geometry is arguably not a priority and certainly should not come at the expense of accessibility.

These tradeoffs are well worth the design's advantages over the preceding two iterations. Compartmentalization enables two core features. Firstly, energy flow can be depicted in a straightforward manner, which then permits the energy-centric theme to more cohesively tie the MGs, batteries, and EEs together, allowing for the system to be more easily understood. Secondly, same-bus components can be compressed visually, which not only reduces clutter during normal operation alleviating cognitive load, but also renders malfunctions and deviations from the average more obvious.

Combined with other improvements presented above, these features create a more readable display.

VII. Conclusions

As the scope of this project did not include any formal pilot evaluation, no conclusion can be made regarding the human factors aspects of the display. Nevertheless, a number of takeaways and solutions can be garnered from the design process:

1) It *is* feasible to fit a hybrid-electric system onto a synoptic display provided that the designer judiciously selects which information to display and delivers the information qualitatively instead of alphanumerically. As automation becomes more prevalent, the type and quantity of information displayed must be more stringently filtered than with conventional synoptic displays. Using an energy-focused theme can help filter out unnecessary parameters.
2) For qualitative indicators, the considerable multiplicity of similar components in the hybrid system should be taken advantage of by compressing information and only displaying diverging readouts. This not only renders the display much easier to read under normal conditions, but also downsizes the depiction of the architecture so that it can fit within the display.
3) For quantitative readouts, averaging outputs, such as EE power, is essential due to the multitude of SUSAN's components. Without averaging, the readouts would occupy excessive space. Digital readouts must be selectively averaged when a battery fails to accurately provide usable energy. For similar reasons selective averaging is also applied to MGs and EEs.
4) Although color-coding was extensively experimented with to a level that breached industry convention, bus-dependent color-coding was found unnecessary and conventional color-coding can largely be adhered to in the final design. Theoretically the colored background on the final HESD can be removed without hindering functionality.
5) The traditional manner of depicting components on the display based on their physical arrangement presented two problems: It inhibited symbology from being fully compressed and also rendered labeling each component infeasible within the available space, which created critical accessibility issues. The unorthodox manner of compartmentalizing components on the same bus was adopted so that they can share a single label. This is necessary for the final HESD concept to be liberated from the reliance on color-coding.

This paper documents the design process and justifies the displays not only for SUSAN's flightdeck, but also more broadly to offer solutions to the same challenges that will undoubtedly be encountered by those who work on hybrid-electric aircraft in the future. While these concepts have not been evaluated by human factors experts, we nonetheless recognize that the final HESD concept still possesses certain drawbacks. The displays are not intended as an authoritative standard that prescribes the design of future HESDs. Rather, we hope to suggest as many ideas as possible to those in the industry who will continue to advance hybrid-electric aviation.

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